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# Lunar Helium-3 and Fusion Power

*Proceedings of a workshop sponsored by  
the NASA Office of Exploration and  
the Department of Energy Office of Fusion Energy  
and held at  
the NASA Lewis Research Center  
Cleveland, Ohio  
April 25 and 26, 1988*



National Aeronautics and  
Space Administration

**Scientific and Technical  
Information Branch**

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## FOREWORD

The NASA Office of Exploration, with help from the Office of Fusion Energy, Department of Energy, sponsored the "NASA Lunar He-3/Fusion Power Workshop." The meeting was held to understand the potential of using  $^3\text{He}$  from the Moon for terrestrial fusion power production. The meeting brought together fusion and mining specialists from academia, industry, and the government. It provided an overview, two parallel working sessions (lunar mining and fusion power), a review of the sessions and discussions.

The lunar mining session concluded that mining, beneficiation, separation, and return of  $^3\text{He}$  from the Moon would be possible, but a large-scale operation and improved technology will be required.

The fusion power session concluded (1) that  $^3\text{He}$  offers significant, possibly compelling, advantages over fusion of tritium, principally increased reactor life, reduced radioactive wastes, and high-efficiency conversion, (2) that detailed assessment of the potential of the D/ $^3\text{He}$  fuel cycle requires more information, and (3) that although D/T fusion is most near term, D/ $^3\text{He}$  fusion may be best for commercial purposes.

Discussion sessions highlighted issues related to politics, international and inter-agency cooperation, and the environment.

On the basis of several concepts generally agreed-upon at the workshop:

1. that D/ $^3\text{He}$  fusion research is in an early stage,
2. that the D/ $^3\text{He}$  cycle has a low priority in the DOE fusion power program (in fact, there are no directed efforts on D/ $^3\text{He}$ ),
3. that D/ $^3\text{He}$  fusion power will eventually be required,
4. that D/ $^3\text{He}$  fusion offers commercial and environmental advantages over the D/T cycle,
5. that lunar mining of  $^3\text{He}$  is feasible,

possible courses for agency action could include:

1. NASA studying the mining and return of lunar  $^3\text{He}$  as a program option,
2. NASA joining with DOE to assess the potential for D/ $^3\text{He}$  fusion and to plan follow-on activities,
3. if the science and the national-need warrants it, developing a cooperative program between NASA and DOE to return lunar  $^3\text{He}$  to Earth for terrestrial fusion power.

Edmund J. Conway  
Executive Secretary

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## DISCUSSION PANEL

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The panel was composed of five people who offered their thoughts on broad questions posed to them as part of this workshop. Each gave a short talk, designed to stimulate questions and discussion. This report is based on notes taken during the presentations and the ensuing discussion.

Michael Duke, NASA

A key question is the environmental impact on the moon of large scale mining operations there. (The presentation was based on a chart which is reproduced below, with the title LUNAR ATMOSPHERE.) The message was, a moon-wide permanent atmosphere could develop over a long time.

Donald Kummer, MDAC

While much was made of the incompatibility of the  $^3\text{He}$  and oxygen recovery processes, there is also much similarity. The two processes could be optimized to work with each other.

The possible use of  $^3\text{He}$  to make tritium could be seen as an arms issue. Also, the economic advantage of using  $^3\text{He}$  from the moon for a fusion fuel, may become a worry to other nations.

Although  $^3\text{He}$  has harder physics to achieve fusion, what is far more important, is that it offers easier technology and easier commercialization.

Not international tension but international cooperation could characterize the activities leading to  $^3\text{He}$  fusion power. Both energy and space have good track records in cooperation. Perhaps we can continue and build on this.

To NASA,  $^3\text{He}$  may have an economic benefit: it may be crucial in convincing the public and Congress that return to the moon is important.

$^3\text{He}$  from the moon requires a joint NASA/DOE plan, with clear enough objectives to have milestones. Such a plan should provide for periodic assessment of the question: should we get  $^3\text{He}$  from the moon and how should we use it?

Robert Iotti, Ebasco

Representing an A & E Firm, this speaker offered the perspective of the end-user: economics. The economic advantage of fusion power is far from clear.

While the fusion community talks of commercializing D/T reactors, other segments of the government are developing a new fission reactor to produce tritium at a cost of \$10 K/gram.

Fusion research goes on, but we do not have a design for a commercial fusion reactor. Such a design is just a first step to establishing the economics of fusion power.

Operating costs for a D/T reactor will be very significant. Based on what we know of the physics, the operating costs could



Based on what we know of the physics, the operating costs could be much lower for a D/<sup>3</sup>He reactor.

Licensing of fission reactors is running approximately half the capital cost. We should expect similar results for fusion.

Users need absolute costs, not relative costs. For them to be serious about D/<sup>3</sup>He fusion power, at very least, we need an assessment of the schedule for a commercial <sup>3</sup>He reactor.

An important question from the user's perspective is: how likely is it that the lunar <sup>3</sup>He fuel supply would be interrupted, causing disruption in fusion power production? An interruption could occur as the result of an accident. A closely related question is: who would be the supplier/insurer of the fuel, government or industry?

What is the impact of the concept of obtaining a fusion fuel, <sup>3</sup>He, from the moon? It may sensitize the U.S. community to the importance of power for the future. The communities in Japan and in Europe are already sensitive.

Stephen Dean, Fusion Power Assoc.

There are three necessary and sufficient conditions required for fusion power to become a reality:

1. Systematic progress coupled with public understanding of that progress. This condition has been fulfilled so far. There is little doubt that it will continue. For D/<sup>3</sup>He, we need a clear increase of a factor of four in plasma temperature and a factor of four or five Tau (density, confinement time product), but we can expect to eventually achieve this.
2. A reactor concept that someone would want. We do not have this now! <sup>3</sup>He may be the basis for a good reactor, the kind a customer might want. We have no detailed design yet which would underlie economic studies. However, in dealing with alternate fuels, remember there are alternates to tokomaks.
3. A long term energy supply problem which would require the development of new energy sources such as fusion. We are speaking of a fifty to two hundred year time frame. Electrical power is a trillion dollar business. To change such a business, there must be money in technology. That money must foster a variety of technologies. It is unrealistic to believe that fusion can be the only winner.

Fusion of <sup>3</sup>He is not widely accepted in Europe or elsewhere. It is a radical departure from current wisdom to think of D/<sup>3</sup>He displacing D/T. Some of the people at this meeting are way ahead of their time. They have a big selling job ahead.

If D/T is commercialized first, <sup>3</sup>He may still be useful for concepts like gaseous breeding of tritium.

There is a world-wide fear of fission reactors. However, fission reactors are probably acceptably safe. D/T is safer than

fission and D/<sup>3</sup>He appears to be still safer.

Europe and Japan may be the first to use fusion power, because their needs for energy sources exceeds ours.

A hope of fusion was that it could reverse the international instability generated by the oil embargo. With the main consumable fuel (D) available in the sea and thus not the property of any nation, D/T fusion would contribute to world stability. If fuel for fusion reactors comes from the moon, then energy generated international instability may accelerate.

H. Schmitt, Consultant

As a economic geologist, this speaker focusses on the question, can a mineral be brought to market for a profit.

If there were much <sup>3</sup>He on earth, we would be further into D/<sup>3</sup>He research and development.

There is much fossil fuel on earth. Technology and price will make it available for fuel. (It is probably more valuable to mankind as a raw material for the petrochemical industry.)

There are no show-stoppers to lunar mining for <sup>3</sup>He. There is much relevant experience on earth which gives us confidence that the job can be done. However, we need to establish the cost of returning it in quantity to earth.

NASA and DOE communities need to begin to cooperate if this country is to take advantage of the window of opportunity for moving toward low cost fusion power in the future.

For the U.S., a major hurdle is how to address politically issues of the future, as they are effectively treated in many other countries. It may be impossible to work such issues because our political system is responsive to short term interests.

How can the world avoid a repeat of problems like the current tensions around the Persian Gulf? U.S. enterprise, which could provide several independent fuel sources is a possibility. International management of the resource is also possible, an Intel-sat management approach could be a model.

## LUNAR ATMOSPHERE

### Total atmosphere contains:

CO<sub>2</sub>                      5200Kg  
Ne, Ar, He                <500 Kg

### Natural atmospheric variation (molecules/cc.)

	<u>Day</u>	<u>Night</u>
H <sub>2</sub>	4x10 <sup>3</sup> cm <sup>-3</sup>	1.2x10 <sup>4</sup> cm <sup>-3</sup>
<sup>4</sup> He	2x10 <sup>3</sup>	4x10 <sup>4</sup>
CO <sub>2</sub>	6x10 <sup>5</sup>	<10 <sup>3</sup>

### Important processes

Solar wind flux of He - 8 mg/sec over entire lunar surface.

- \* Thermal escape from ballistic trajectories.
- \* Photoionization - escape or implantation.
- \* Adsorption - removes gases at night.

### Implications of Lunar Mining.

Lunar regolith trapped gas approximately 0.1g/Kg.

If 10% of trapped gas is released by agitation  
=> 10 g/tonne.

100,000 tonnes regolith /yr. releases 10<sup>3</sup>Kg, roughly  
equivalent to entire atmosphere.

Local gas release causes effects that rapidly extend as far as ballistic trajectories of atoms (hundreds of Km). Adsorption/re-implantation removes gases from the atmosphere, particularly at night.

Solar wind (photoionization) losses diminish if the atmosphere is thick. Thus, at a constant gas emission rate the atmosphere thickens, the loss rate diminishes, leading even more rapid increase of atmospheric density.

- \* Need better understanding of the relation between gas release and atmospheric properties.

## OPEN DISCUSSION

Edmund J. Conway

Office of Aeronautics and Space Technology  
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The format for this session was: Questions were posed from the floor, answers were offered both by the panel and from the floor. A complete correlation of names with comments was not maintained, so for uniformity, names are not used in this session.

1. Comment on the political and legal aspects of lunar mining.

- \* Only six nations have signed the U.N. space treaty, and this includes none of the major space players. There is a phrase in the treaty which defines space and what is in it as the "common heritage of all man-kind". This concept appears to make all space activities illegal. However, there is a concept, functional sovereignty, currently a debatable point among space lawyers, which seems to give each nation freedom to act in space.

2. How best get more attention to be the subject of this workshop?

- \* One suggestion is a joint NASA/DOE sponsored international topical conference. This would make our subject more visible and would stimulate interest. (The possible legal prohibition on returning  $^3\text{He}$  from the moon could be a cloud for the fusion community.)

- \* The international community cannot be prohibited from thinking of lunar  $^3\text{He}$  and the related legal issues. However, if Europe and Japan build the first fusion reactors, the U.S. may become the fuel supplier.

- \* Public opinion could be mobilized if a demonstration of  $^3\text{He}$  fusion were achieved. (It would show the oil cartel!) Fusion has been decelerated by international effects. Very long range goals have been chosen for fusion.

- \* We are dealing with a time window, once NASA decides on its advanced mission program in the early 1990s, if the moon is not one of the main objectives, lunar  $^3\text{He}$  is lost! We know that a). D/ $^3\text{He}$  fusion is highly desirable, b). no lunar mining show-shoppers exist, c). NASA is planning its next goals for early in the next century. We need a schedule to use this window of opportunity.

- \* DOE and NASA should have an official joint program! This is not unprecedented, recall the joint Space Nuclear Propulsion Office. The DOE Office of Fusion Energy will probably not create a thrust, but if the two agencies get together, it may happen.

- \* Lets develop a recommendation which requests NASA and DOE to establish a plan to perform these activities.

- \* Interagency offices can be a problem to run. They are usually the first to be cut when money becomes tight. Traditionally, interagency offices have the least continuity.

- \* Representatives from the agencies will try not let the



subject of  $^3\text{He}$  drop.

3. Should we establish a minimum concentration for  $^3\text{He}$  in lunar soil as the lowest concentration worth mining?

- \* I recommend a threshold somewhere between 150 ppm and 100 ppm.

- \* (Group discussion opposed this threshold because of the very indirect way (through energy concentration in coal ore on earth) the threshold was derived. Recommendation not accepted.)

4. From NASA's point of view, does the  $^3\text{He}$  on Jupiter offer a good backup to  $^3\text{He}$  from the moon?

- \* NASA's preliminary planning calls for a lunar base ten times to one hundred times smaller than is needed to mine  $^3\text{He}$ . The lunar base could build toward  $^3\text{He}$  mining. We do not know of any major sources of this isotope in the solar system except on the moon and on Jupiter. However, the agency is not seriously considering going to Jupiter.

- \* There are unexplored reserves of natural gas which may contain large quantities of  $^3\text{He}$ .

- \* These natural gas reserves may overshadow  $^3\text{He}$  fusion. However on the moon, one may want to make many things and D/ $^3\text{He}$  fusion may provide the power. It could be a cheap way to get water and other things to the moon.

- \* DOE is wedded to tokomaks, but this concept is not worth much to NASA. There are compact fusion concepts using alternate fuels which may be useful for space power and propulsion.

5. What are the Soviet approaches and potential problems?

- \* The Soviets are as capable as we are, so they could develop a fusion technology by themselves. However, historically, the USSR has been open and cooperative about fusion research. They have also been a driving force in the scientific advancement of fusion. Their policy seem to be to work cooperatively, they are not trying to outrun us.

- \* The USSR program aims at using fusion to breed fissile fuels.

- \* Japan may intend to pass us by! Their industries are positioned, and fuel is in great need in Japan.

- \* There is much interest in  $^3\text{He}$  in Japan.

- \* Industries in Japan are also interested in the moon. They are doing lunar base work on their own.

- \* The Soviets have a vision of their leadership among nations. They have a ten year lead in space experience. However the Japanese have the greatest momentum.

6. What happens if by the year 2000 we are able to burn  $^3\text{He}$ ? Is a lunar  $^3\text{He}$  program ordained?

- \* We must consider the political priorities. The executive and legislative branches of the government will be intimately involved in any final decision. NASA must participate in that decision.

\* Get involved in the election of candidates who will support research and energy. The political time scale is short. Get involved before the next election.

\* High Energy Physics gets large accelerators funded by Congress. What do we do wrong?

\* Maybe some pessimism comes through the agencies!

\* There are mechanisms to circumvent the pessimism in DOE. Use the Magnetic Fusion Advisory Committee (MFAC). Actions going this route need 6 to 9 months to be put on the agenda and then be discussed. MFAC offers a way to broaden the DOE management basis for making decisions.

7. Are there other lunar problems besides atmosphere generation?

\* None that we foresee.

8. How early do we need to address any issues?

\* This country needs a political commitment! We must resolve important questions in favor of the majority of the people.

The chairman called an end to the formal open discussion, and numerous informal discussion groups formed.

## OBJECTIVES AND QUESTIONS TO BE ADDRESSED

Please read through the following information to better understand the purpose of this workshop and to consider the questions to be addressed in the working groups and plenary session.

**Goal:** The goal of this workshop is to provide information for assessing the feasibility, practicality, and advantage of mining Helium-3 from the lunar regolith to provide fusion power on Earth.

**Focus:** The focus of this workshop will center on two aspects: Terrestrial Fusion Technology, specifically as pertains to Helium-3 applications, and the technology required to mine Helium-3 from the lunar surface.

### Objectives:

- The Fusion Technology participants (Working Group I) will assess the practicability of employing Helium-3 to advance terrestrial fusion power technology either as a main fuel or as a blanket material.

- The Space Mission participants (Working Group II) will consider the viability of a lunar mining operation with respect to cost, enabling technologies, and timeframe.

- The workshop as a whole will consider whether the mining of Helium-3 for terrestrial fusion power applications could be a sufficient rationale for returning to the moon.

### End Product:

Transactions (loose-leaf) printed from prepared material, view graphs, rapporteur and minority reports, and plenary discussions summarized by executive secretary.

Questions to be addressed by Working Group I:

I-1. What is necessary to validate the feasibility and practicality of D/He-3 fusion and He-3 breeding of Tritium?

I-2. How does D/He-3 compare to the D-T fuel cycle?

- (a) physics requirements
- (b) radiation safety
- (c) waste removal and storage
- (d) power generation
- (e) timeframe to principle demonstration and commercialization
- (f) cost

I-3. How does He-3 compare to Lithium as a blanket material in D-T fusion?

- (a) radiation safety
- (b) waste removal and storage
- (c) cost

Questions to be addressed by Working Group II:

II-1. How much He-3 is there on the moon and where is it?

- (a) What are the theoretical projections of He-3 supply and the most likely candidate sites for mining?
- (b) What is the minimum concentration of He-3 in the lunar surface for economical mining?

II-2. How do we recover the He-3?

- (a) In what ways can the techniques proposed for mining Lunar oxygen be adapted for He-3 recovery and evolution?
- (b) What power would be required for Helium-3 evolution from the lunar soil?
- (c) What is the order of magnitude of cost to mine He-3 on the Moon?

II-3. How do we transport the He-3 to Earth?

- (a) What processes would be required to liquify and store the Helium-3 after recovery?
- (b) What infrastructure and transportation capabilities must be in place before lunar mining can be reasonably initiated?
- (c) What is the order of magnitude of cost to transport He-3 to Earth?

Questions to be addressed by Plenary Session (Day 2):

P-1. Are there ramifications (legal, environmental, political, scientific, economic) to mining He-3 from the moon? Are there additional ramifications in using He-3 on Earth?

P-2. If a viable and practical method for obtaining He-3 from the Lunar surface could be made available, what impact would this have on the fusion community, the United States, and the world?

P-3. Are there important questions or factors that have not been addressed by this workshop?



## AGENDA

Monday, April 25, 1988

- |          |   |
|----------|---|
| 8:00 am  | Sign-in & refreshments  |
| 8:30 am  | Introduction to Workshop and Agenda Review  |
| 8:45 am  | Explanation of Code Z Charter and Workshop Rationale--by Edward Gabris  |
| 9:00 am  | Concepts Overviews: <ul style="list-style-type: none"><li>• Lunar Source of <math>^3\text{He}</math> for Terrestrial Fusion Power--by G. Kulcinski</li><li>• Development of Helium-3 Breeding of Tritium--by D. Steiner</li></ul>   |
| 10:30am  | Break. Parallel Sessions begin.   |
| 10:45 am | Instructions to Working Groups by Group Chairperson   |
| 11:00 am | Parallel Session/Background Papers <ul style="list-style-type: none"><li>WORKING GROUP I -- George Miley - Chairman<br/>Gerald Epstein - Rapporteur<ul style="list-style-type: none"><li>• Status of Fusion Research Power and Implications for D/He-3 Systems--by G. Miley</li><li>• Strategy to Bring D/He-3 Research to Maturity--by J. Santarius</li></ul></li><li>WORKING GROUP II -- Michael Duke - Chairman<br/>Jeff Plescia - Rapporteur<ul style="list-style-type: none"><li>• Lunar Resource Program--by David McKay</li><li>• Process and Energy Costs for Mining Lunar Helium-3--by I. Sviatoslavsky</li><li>• Economic Geology of the Lunar Maria--by H.H. Schmitt</li></ul></li></ul> |
| 12:30 pm | LUNCHEON  |

1:30 pm	Parallel session/Discussion of W.G. Questions
2:45 pm	Break
3:00 pm	Parallel session/Continued Working Group Discussions
5:30 pm	Adjourn

**Tuesday, April 26, 1988**

8:30 am	Reports by Rapporteurs to Plenary Group
9:30 am	Discussion of Rapporteurs Reports
10:00 am	Break
10:15 am	Panel Discussion of Plenary Group Questions
11:00 am	Discussion of Plenary Group Questions (P-1 through P-3)
12:30 pm	Adjourn

# FUSION POWER WORKING GROUP REPORT: D-<sup>3</sup>He FUEL CYCLE

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## I. SUMMARY

There appear to be significant potential advantages to a D-<sup>3</sup>He-fueled fusion reactor. These advantages could become compelling with respect to environmental, safety, licensing, and public acceptability.

The physics requirements for a D-<sup>3</sup>He machine are challenging. Information regarding the behavior of plasmas under conditions sufficient to burn D-<sup>3</sup>He will become available as existing large machines (TFTR, JET, etc.) yield further experimental results. It is believed that additional physics questions regarding the D-<sup>3</sup>He fusion reaction could be resolved with relatively modest fractional increases in the cost of planned future domestic and international devices such as CIT and NET/ITER.

The overall value of making these modifications to enable D-<sup>3</sup>He reactions to be studied depends on how well fusion physics scales to bigger machines. With reasonably favorable scaling, D-<sup>3</sup>He could ignite in an augmented NET. Similarly, D-<sup>3</sup>He could obtain a Q of 2 (some would argue more) in CIT. (A Q of 2 in D-<sup>3</sup>He would be equivalent to a Q of 10 in D-T in terms of fusion power coupled back to the plasma.) Although estimates were presented to the working group that the necessary modifications would impose a cost penalty of only approximately 10 percent, the basis for these estimates was not evaluated by the group and the group did not come to consensus as to the cost or the likelihood of making such changes to NET.

Many engineering problems appear to be simplified or eliminated with D-<sup>3</sup>He, arguing for a shortening of the time needed to commercialize fusion once the physics is proven. On the other hand, if the more difficult physics of the D-<sup>3</sup>He reaction were to be accommodated by a larger and more expensive machine, the increased cost could delay commercialization.

D-<sup>3</sup>He should not at present be seen as an alternative to the present D-T program--we are not facing an "either/or" choice. D-<sup>3</sup>He is a very attractive fuel cycle, but other D-T options (low activation materials, etc.) exist to provide environmental/safety/licensing benefits. There is some disagreement as to how effectively a D-T machine could provide

the benefits of D-<sup>3</sup>He. One of the difficulties in assessing how important D-<sup>3</sup>He's advantages could be over D-T is our inability to predict the environmental, safety, and public acceptability standards that will be required of future fusion reactors.

## II. STATE-OF-THE-ART FOR D-<sup>3</sup>He ANALYSIS

Hypothetical fusion reactors using the D-<sup>3</sup>He fuel cycle have been envisioned for years. However, until very recently, these exercises have only been of academic interest due to the lack of a <sup>3</sup>He resource base. Recognition that the moon offers a vast and potentially recoverable <sup>3</sup>He resource has stimulated active and exciting analysis of D-<sup>3</sup>He fusion. We have just begun to scratch the surface in exploring D-<sup>3</sup>He's potential, and great returns can be expected from additional work.

Much of the present discussion was guided by preliminary studies of how to fit D-<sup>3</sup>He into the international tokamak program. Little analysis has been performed for alternate confinement (both magnetic and inertial) techniques, although the possibility of combining small, high-beta confinement with favorable D-<sup>3</sup>He features is potentially a high leverage route. Applications other than terrestrial electric power (e.g. space propulsion and space power) were considered very interesting but beyond the scope of this meeting.

Some working group members argued that the question of alternate concepts was distinguishable from the question of D-<sup>3</sup>He fuel in that if these concepts have advantages for D-<sup>3</sup>He, they likewise have advantages for D-T. Others thought that high-leverage alternate concepts took on special significance in the light of the potential advantages and the physics requirements (in particular the high-beta requirement) of the D-<sup>3</sup>He reaction.

Fusion mainline progress has been steady but slow. The Technical Planning Activity (TPA) has outlined a program reaching a feasibility assessment for D-T fusion by about 2005. (Given slippage in projected program budgets since the TPA study was done, it was argued more realistically that the date should be delayed.) TPA also presented plans for development of a number of alternate concepts that may make more sense for D-<sup>3</sup>He. Are these alternatives sufficient, or do we need new ones to make the most use of the advantages of D-<sup>3</sup>He?

Within the fiscal and programmatic constraints of the present DOE fusion program, new concept development and acceleration of existing alternate concepts are difficult. Therefore, there is an incentive to see what we can find out from existing and proposed D-T experiments.

Much more tokamak scaling and confinement data will be obtained as present experiments (TFTR, JET) continue to



operate. This data, while not directly applicable to advanced tokamaks and alternate concepts, still will have strong implications for the physics potential for D-<sup>3</sup>He: if D-T scaling is found to be marginal, D-<sup>3</sup>He must be viewed as unlikely without development of concepts offering radically different scalings.

Major existing experiments will, at some stage, burn D-<sup>3</sup>He anyway, providing much information at little additional expense. However, the role of these D-<sup>3</sup>He experiments in the context of the D-T experimental program is to study radiofrequency heating of the minority <sup>3</sup>He species. The physics studied by heating a very dilute <sup>3</sup>He minority to very high temperatures may not address the major confinement questions posed by a D-<sup>3</sup>He fuel cycle.

There is a possibility that design modifications to CIT or NET/ITER could yield a wealth of useful data regarding D-<sup>3</sup>He. Since the nuclear cores of these machines constitute only a fraction of their total cost, the cost of modifying their cores would be "diluted" by the fixed cost of the remainder of their facilities. However, no quantitative analysis of either the cost of the necessary modifications to the CIT or NET/ITER cores or of the fraction of the CIT or NET/ITER total costs that would be contributed by their nuclear cores was presented to the working group.

Further studies and systems analyses are important to better define the potential benefits of D-<sup>3</sup>He. Two different cases should be looked at:

- a) a commercial reactor study, possibly including both advanced tokamak and high-leverage alternate concept designs, and
- b) studies of modifying CIT or NET/ITER to provide leeway to burn D-<sup>3</sup>He.

Although distinct, these two different types of studies are related. They have different timescales, and a successful commercial reactor study may increase the motivation to accept modifications to the CIT and NET/ITER designs.

### III. RELATIVE COMPARISON OF D-<sup>3</sup>He AND D-T PHYSICS AND ENGINEERING ISSUES

Physics is harder for D-<sup>3</sup>He. Plasma temperatures and confinement parameters (product of plasma density and confinement time) needed to burn D-<sup>3</sup>He are each about 4 times higher than needed for D-T; the required beta (ratio of plasma pressure to

magnetic field pressure) depends on the magnetic field but would probably have to be several times for D-<sup>3</sup>He than for D-T. Alternatively, as a working group member indicated after the workshop, the peak reactivity of D-<sup>3</sup>He is about half that of D-T, and it occurs at a temperature 5 times higher. Therefore, at constant plasma beta and magnetic field, the power density of a D-<sup>3</sup>He reactor would be  $2 \times 5^2$  or 50 times lower than that of a D-T reactor. To achieve the same fusion power, it would require a plasma volume 50 times larger (at constant beta and magnetic field) or a magnetic field 2.6 times higher (at constant beta and plasma volume). However, see the discussion of power density scaling given below under the heading "Power Density".

If tokamak betas cannot be improved substantially, development of alternate confinement concepts with inherently higher betas may be necessary for practical D-<sup>3</sup>He reactors. Exactly what the increased physics requirements for D-<sup>3</sup>He imply in terms of reactor design, feasibility, and desired confinement approach is uncertain and awaits additional data and systems analyses.

**Fueling**--Deep internal pellet fueling of a D-<sup>3</sup>He reactor will be even harder than for a D-T reactor due to the higher plasma temperatures and the difficulty of freezing <sup>3</sup>He. However, it will likely be impossible to get deep internal pellet fueling even for D-T reactor plasmas; it is also unclear that deep fueling will be necessary. Therefore, additional fueling techniques such as surface fueling or plasma injection are likely to be developed for D-T reactors. The efficacy of these techniques depends on MHD phenomena but not per se on electron temperature or plasma isotopic composition. Therefore, to lowest order their difficulty should be approximately the same for D-<sup>3</sup>He as for D-T.

**Power Density**--The traditional  $(\beta)^2 B^4$  power density scaling discussed in the "Physics" section above gives only part of the story in looking at the power density of a D-<sup>3</sup>He reactor. Power produced per volume of plasma is less relevant than total reactor electric power divided by total reactor core mass. Core mass of a D-<sup>3</sup>He reactor is lessened by the reduced shielding requirements and the possibility of direct conversion of fusion power to electricity. The net results from systems studies to date indicate that the various factors tend to cancel, possibly giving D-<sup>3</sup>He reactors power densities comparable to D-T. Advanced high-field magnets and some alternate concepts could possibly facilitate the prospect for D-<sup>3</sup>He.

**Heat Flux** on the first wall will be approximately the same as that for D-T due to the counterbalancing effects of more power in charged particles and a lower power density. (There is quite a bit of margin in current D-T reactor designs since neutron wall loading, rather than heat flux, has been the limiting factor.) With higher plasma temperatures in D-<sup>3</sup>He reactors, the collector

plates of an electrostatic direct convertor would see a higher energy plasma.

Materials issues seem to be greatly relaxed for D-<sup>3</sup>He reactors. Neutron wall loading is a factor of 50 lower, buying a great deal in terms of reduced neutron damage to reactor materials, extending reactor component lifetime, reduced activation, improved reliability, and reduced radioactive waste volume. If realized, these benefits could be extremely significant in terms of fusion's environmental and safety characteristics and acceptability to utilities and the public. See the section below on "Safety, Environment, Investment Risk, Licensing, and Acceptability."

Plasma Heating techniques are similar for D-<sup>3</sup>He and D-T: higher temperatures are required for D-<sup>3</sup>He and the appropriate heating requirements are likely to be larger.

Current Drive--D-<sup>3</sup>He and D-T have similar requirements. Much higher plasma currents are required for D-<sup>3</sup>He, but the drive efficiencies should be higher at the higher D-<sup>3</sup>He plasma temperatures. Determining the net balance between these factors requires further work.

Efficiency of D-<sup>3</sup>He reactor is potentially much higher than that of a D-T reactor due to the possibility of directly converting fusion energy into electricity. Efficiencies of up to 70% have been modelled. However, to achieve these efficiencies, further work must be done in developing systems to convert plasma energy directly and economically into electricity. Possible approaches include

- direct electrostatic conversion (which is not applicable to toroidal geometries)
- direct electromagnetic conversion, and
- very high temperature thermal cycles using microwave heating of media external to the reactor

Direct conversion technologies should be vigorously pursued. Most of the issues involved are generic. Although some would be avoided in select alternate (non-tokamak) alternate approaches, other issues would appear.

Safety, Environment, Investment Risk, Licensing, and Acceptability--These issues are crucially important and possibly compelling in terms of fusion's overall commercial feasibility. A D-<sup>3</sup>He reactor should be more attractive with respect to these attributes than a "conventional" D-T reactor due to D-<sup>3</sup>He's greatly reduced tritium inventory, activation of the reactor structure, afterheat generation from radioactive decay after shutdown, and radioactive waste volume. (D-<sup>3</sup>He reactors will produce from 1 to 4 percent of their energy via D-D and D-T

reactions, which produce neutrons. Therefore, the activation product inventory and afterheat of a D-<sup>3</sup>He reactor will be about 1-4 percent that of an equivalently sized D-T reactor, if a D-<sup>3</sup>He reactor of similar volume becomes feasible.) Some working group members pointed out that a D-<sup>3</sup>He fusion reactor could potentially be built with non-nuclear grade materials throughout, leading to significant cost savings. All working group members agreed that the potential attributes of a D-<sup>3</sup>He fusion reactor would be highly desirable; there was some disagreement as to how well D-T reactors could also approach high levels of safety assurance and environmental acceptability. Some panelists thought that D-T would be environmentally unacceptable; others believed that D-T designs as they are now are already quite good and with a little effort can be made still better. (A study on the issues of safety, environment, etc., which included D-<sup>3</sup>He has been published [UCRL-53766-SUMMARY].)

#### IV. NEAR-TERM PLASMA VALIDATION ISSUES

Continued development of theoretical/empirical confinement scaling laws with emphasis on the high-temperature region will increase our understanding of the feasibility of D-<sup>3</sup>He reactors. It is particularly important to determine whether the degradation in confinement that has been observed with non-ohmic plasma heating is due to plasma temperature or to the injected power. If confinement degradation depends on temperature, rather than on injected power, it will be much more difficult to extrapolate from the 15 keV ion temperatures needed for D-T fusion to the 60-80 keV ion temperatures needed for D-<sup>3</sup>He.

Cyclotron radiation loss at the hotter D-<sup>3</sup>He plasma temperatures becomes important if the radiation is not self-absorbed by the plasma (e.g. if the plasma operates at low beta.) At low beta, wall reflectivity becomes important. This reflectivity may be affected by other design constraints such as graphite first wall coatings, holes in the first wall, and the need to avoid conductive wall material to avoid damage in tokamak disruptions. Reflectivity data in the 1000 - 2000 GHz range is needed.

#### V. QUESTIONS

At what point do the "minor" changes proposed for CIT and NET/ITER become major? This will affect how willing people will be to consider these changes. (Agreeing on common design goals in a large-scale collaboration is tough enough as it is.) Even if no modifications are done, use of D-<sup>3</sup>He in machines designed for D-T may be quite useful and should be explored.

What sort of opportunities/requirements are there to do



research between the near-term results that will be obtained from TFTR and JET and those obtainable from modifying the design of yet-to-be built devices such as CIT and ITER?

What are the important time windows? CIT and NET/ITER designs will probably be frozen before much D-T data from TFTR and JET will be available. The longer this data takes to obtain, the harder it will be to argue for changes to CIT or NET/ITER.

How much should D-<sup>3</sup>He reactor design be limited to technologies now considered feasible or practical? Consider the evolution in magnet engineering over the last decade even without use of higher-field superconductors. With substantially improved magnet capability (say 18-20 Tesla instead of 8 or so), what had previously been seen as conventional wisdom with respect to questions such as mass power density scaling may get turned upside down. At lower fields, the mass power density of a D-T reactor design is higher than that of D-<sup>3</sup>He; at higher fields, the relative reduction in shield and blanket mass for D-<sup>3</sup>He designs and neutron wall loading limitations for D-T could give D-<sup>3</sup>He the edge. This design estimate, however, assumes continued development in magnet technology that permits increased magnetic field to be obtained without degrading the magnet current density.

The working group did not achieve consensus as to the relative timescales for commercializing D-<sup>3</sup>He and D-T reactors. Relative estimates requires comparing two highly uncertain schedules. The timescale of D-<sup>3</sup>He commercialization appears to be consistent with that of the availability of lunar <sup>3</sup>He.

Commercialization timescales depend significantly on how important materials qualifications data will be. Many engineering problems may be simplified or eliminated with D-<sup>3</sup>He, arguing for a shortening of the time needed to commercialize once the physics is proven. However, other engineering issues are introduced with D-<sup>3</sup>He:

- Some tradeoffs may occur (which further systems studies are needed to quantify), such as the increased wall erosion in a D-<sup>3</sup>He reactor due to particle bombardment and high heat flux over a longer first wall lifetime.
- Direct conversion technology for D-<sup>3</sup>He reactor concepts is much more important than it is for D-T.

### $^3\text{He}$ AS A TRITIUM BREEDER MATERIAL

Using  $^3\text{He}$  as a tritium breeding material introduces no new feasibility and practicability issues and ameliorates some of the existing issues. Current concepts for  $^3\text{He}$  breeder blankets stress use of beryllium neutron multipliers. Although they do not require significantly more beryllium than other blanket designs requiring multipliers, limits on the overall availability of beryllium may necessitate consideration of alternate multiplier materials. Engineering issues involved with using  $^3\text{He}$  as a breeder material will be easier to resolve than those for lithium breeder blankets.

Using of  $^3\text{He}$ , rather than lithium, for breeding tritium eliminates the tritium that in a solid lithium breeder blanket would be bound to the solid breeder material. In this respect, use of  $^3\text{He}$  improves the safety of the blanket since the eliminated tritium would not be available for release in an accident. However, larger amounts of tritium than would be bound to the breeder material will inevitably be present in D-T reactors in the plasma exhaust, fuel reprocessing, and vacuum systems. Therefore, eliminating the tritium within the lithium breeder material provides only a limited gain in safety. Eliminating the solid lithium breeder material also eliminates the oxygen that serves as a source of carbon-14 production. Reducing the  $^{14}\text{C}$  is more of a waste issue than a safety one.

Use of  $^3\text{He}$  has the added advantage of eliminating the need to develop solide lithium-containing breeder blankets. Eliminating the lithium blanket development has two advantages--a direct advantage of easing blanket engineering, and an indirect effect of possibly improving the reliability and safety of the blanket due to simplified engineering.

The potential payoff for a  $^3\text{He}$  breeder--expressed in terms of how much one would be willing to pay for the  $^3\text{He}$ --is not as high as the potential payoff from implementing a D- $^3\text{He}$  fuel cycle. Whereas the avoided cost of fossil fuel equivalent to the energy content of  $^3\text{He}$  has a value as high as \$2000 per gram of  $^3\text{He}$ , the avoided cost in eliminating the lithium blanket has been estimated as equivalent to a  $^3\text{He}$  price of between \$100 and \$500 per gram. Of course, the technical risk of using  $^3\text{He}$  as a tritium breeder is correspondingly less than the technical risk in implementing a D- $^3\text{He}$  fuel cycle.

The price one is willing to pay for  $^3\text{He}$  will be a determining factor in creating demand for lunar  $^3\text{He}$ . Using  $^3\text{He}$  as a breeder material will not motivate lunar  $^3\text{He}$  recovery to the extent that a successful D- $^3\text{He}$  fuel cycle would. Moreover, the use of  $^3\text{He}$  for breeding tritium prior to achievement of lunar  $^3\text{He}$  recovery must be carefully viewed in terms of the limited  $^3\text{He}$

resources available on earth and the requirements for  $^3\text{He}$  reactor development. Some working group members thought that converting  $^3\text{He}$  into tritium would definitely be a step in the wrong direction.

## LUNAR MINING WORKING GROUP REPORT

Jeff Plescia

Three papers were presented during the morning session: Lunar Resources Program (D. McKay), Processes and Energy Costs for Mining Helium-3 (I. Sviatoslavsky) and Economic Geology of the Lunar Maria (H. Schmitt). After lunch the group reconvened to discuss these presentations and the concepts of lunar mining. The questions originally posed to the group by the conveners (see attached list) were also discussed.

The following notes are intended to convey the general tenore of the discussions rather than minutes of the meeting in the chronologic sense. Repeatedly during the discussions, the same topics were revisited but with different emphasis. So this document is an attempt to compile the relevant points of each of the different topics.

### Space Resources Program

Dave McKay reviewed the NASA Space Resources Program; the program is composed of three aspects (Mining, Transportation, and Processing). Processing is the most active area and includes several small business contracts. Several contracts have been let to study various aspects of the Processing aspects of the program:

Carbotek: Aspen Simulation Lunar Oxygen Production Facility.

Carbotek: Lunar Oxygen Production From Ilmenite.

EMEC Consultants: Dry Extraction of Silicon and Aluminum from Lunar Ores.

Eltron Research, Inc.: Electrochemical Generation of Useful Chemical Species from Lunar Materials.

Advanced Energy Dynamics: Electrostatic Fractionation of Natural and Processed Lunar Solids.

### FUTURE PLANS

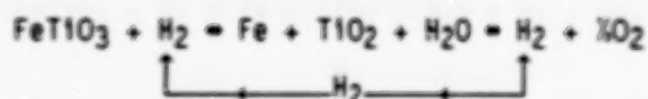
Future plans for the JSC/Code 2 activity include: 1) A SURVEY (from existing data) of lunar and planetary resources describing the availability and volume of those resources; and 2) a production benefit analysis of lunar resources and transportation systems.

### O<sub>2</sub> PRODUCTION

Oxygen production may be the highest priority of the lunar resources program. The O<sub>2</sub> would be used primarily as a propellant. Production would require several small mining pits per year using either a drag-line system or

a ballistic miner. Electrostatic methods would be used for beneficiation of the ilmenite from the regolith.

The chemical reaction to produce oxygen from ilmenite is:



The reaction takes place at 900C;  $\Delta H = +9.7$  kcal/gram mole; equilibrium  $\text{H}_2$  conversion = 7.4% and uses a gas-solid reactor process. The complete process would include: mining, beneficiation,  $\text{H}_2$  reduction and electrolysis, cooling (liquefaction), and transportation.

A production facility capable of  $\text{O}_2$  production of 1,000 tonnes/year would require 2.3 Megawatts (MW) of electric for the reactor, 1.5 MW for mining, and 1 MW for beneficiation. Some He is a by-product of this process, but because 80-90% of the He is discarded during beneficiation, it is not a very efficient He production process. Additional by-products of the process might be bricks as well as other metals.

#### QUESTIONS

Several questions remain which need to be addressed regarding mining operations on the Moon and production of Helium-3. These include:

- 1) What is the concentration of He in the lunar regolith as a function of depth as well as its areal distribution?
- 2) Why is the He abundance in the regolith strongly correlated with the  $\text{TiO}_2$  concentration?
- 3) Can we predict the He concentration on the basis of soil maturity?
- 4) Do concentrations of He (higher than those so far observed) occur in the ancient (highlands) regolith?

#### IGOR SVIATOSLAVSKY PROCESSES AND ENERGY COSTS FOR MINING HELIUM-3 Distribution of Helium-3

He-3 concentration in lunar regolith is about  $9 \times 10^{-3}$  g/tonne (ppm); most of it ( $8.1 \times 10^{-3}$  ppm) is concentrated in the  $<50$   $\mu\text{m}$  size-fraction of the regolith.

#### MINING PROCESS

The regolith would be screened to discard the  $>4\text{mm}$  size fraction. The  $<4$  mm size-fraction would then be subjected to electrostatic beneficiation which would retain only the  $<50\mu\text{m}$  size-fraction. The beneficiated fraction would then be heated to 700C to release the volatiles. The evolved gas would then be compressed for storage.



Regolith would be collected by a bucket-wheel excavator to a depth of 3m. The miner would excavate about 1,258 tonnes of regolith/hour; 3,942 hours/year (daylight) to produce 33 kg He-3/year.

The heat source for volatile release could be solar (thermal). A large 110 m (diameter) solar collector based near the miner would collect solar radiation, focus it, and reflect it to the miner. The mine would have a 10 m dish to receive the reflected solar radiation.

The evolved gas is subjected to a cooling/condensation process to liquify and separate the different species. Cooling takes place during the lunar night to make use of the ambient cold. Hydrogen is removed before cooling. Other gases produced by the process include H<sub>2</sub>O, O<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>, etc. The evolved He is subsequently cooled to 55K for preliminary isotopic separation and then through a cryogenerator (to 1.5K) to achieve maximum He-3 concentration (99%).

### BENEFITS

1 kg of He-3 would provide 10 MW yr of electrical energy. As energy demand increases and fossil fuel availability decreases, the requirement of He-3 should increase.

Factors of merit for Helium-3 fusion are quite high.

$$\frac{600,000 \text{ GJ/kg He-3 (released in fusion)}}{2253 \text{ GJ/kg He-3 (acquisition of He-3)}} = 266 \quad (\text{excludes power plant development costs})$$

$$\frac{600,000 \text{ GJ/kg He-3 (released in fusion)}}{7278 \text{ GJ/kg He-3 (acquisition of He-3)}} = 82 \quad (\text{includes power plant})$$

### SUMMARY

The mining of Helium-3 on the Moon and its use as a fusion fuel on Earth is technically feasible, economically viable, uses state of the art procedures, requires large masses of machinery lifted to the Moon for lunar processing, and has a significant payback (>80).

### Considerations of Mining Helium-3 on the Moon

#### GEOLOGY

We need to know the distribution of high-TiO<sub>2</sub> materials on a global basis so that an optimal candidate mining site can be selected. For that candidate site aspects such as the regolith depth, boulder distribution, grade of the regolith, and regional geologic context would need to be determined.

#### DATA

Some new data might be required. A precursor mission(s) might be required to choose the best site. Although good candidate sites could be selected on the basis of the current data set, it is unknown whether there are better sites or whether the current data base would be sufficient to attract investors.

## ACCESS

An infrastructure would be required to support a lunar mining effort. This would include not only the facilities directly on the lunar surface but also transportation capabilities. The transportation capabilities would be influenced by the support costs of Earth-->Moon and Moon-->Earth transportation, launch vehicles and frequency, flight/delivery risks, etc.

## MINE PLANNING

The terrestrial mining experience base is large and should be tapped. A specific analog to lunar regolith mining would be mining of terrestrial mineral-sand deposits. The grade and distribution of "ore" would need to be known which in turn would require assessments ahead of the miner for planning purposes.

## MINING

The low lunar gravity (1/6 Earth's) may be a problem for the equipment. The machinery may require ballast to achieve the required mass/inertia for mining. Since transportation costs are high, the ballast may have to be supplied from lunar materials.

## ECONOMIC

The costs, pricing, controls, overhead, etc. need to be evaluated for this endeavour. A parametric cost/benefit analysis should be compiled.

## SUPPORT

The context of lunar mining vis-a-vis a lunar base needs to be studied and understood.

### Notes on General Discussion

The afternoon session focused on many aspects of Helium-3 production on the Moon. These aspects include the actual mining, processing, transportation, infrastructure, economics, etc.

## TIMING

For fusion purposes, He-3 could be required on Earth around 2015; the lunar base, as envisioned by Code Z, will begin around 2001.

The issue of establishing a lunar base or a Helium-3 mining operation is complicated by the current procurement regime. Given the oversight restrictions, it is difficult to initiate such a large program with assured, stable funding. Of concern is the timing of a decision to initiate Helium-3 mining - whether it occurs before or after the inception of a lunar base.

## CREW SIZE

The crew might number 3 to 6 during the initial production phase. Later, it would expand to about 20 to 25 people (1/3 of the crew being used in a maintenance capacity). Ultimately, the operation could evolve into a three shift, 24-hr/day work load.

A lunar mining operation will require a much more efficient use of people than terrestrial activities (i.e. a few versus thousands of workers). For lunar mining, manpower is probably the most expensive component; robotics are comparatively cheap. The cost of manpower may also be influenced by the scope of the operation; if large quantities of consumables are produced as a result of the Helium-3 mining, then the costs of supporting the outpost might be lower.

Consumables are provided by the He-3 miner and may affect the economics of the lunar base scenarios. Transportation of people a major cost.

## MINING

Establishing a Helium-3 mining operation can benefit from terrestrial mining experience. There are many operations on Earth that use strip mining techniques to collect distributed surface deposits (laterite soils in Central America used in aluminum production) and/or remove the overburden and then collect a lower stratigraphic layer (coal).

The original suggestion was to mine the upper 3m of regolith, process it, and deposit the material behind the miner. Alternative suggestions were to use a terrace approach so that the miner is exposed for maintenance or such that deeper levels (>3m original depth) could be worked. A concern was expressed about the scale of the operation and at what point it would be visible from the Earth.

The miner would mine approximately  $5 \times 10^6$  tonnes/year. but since it operates only half-time (during daylight hours) it actually must be capable of mining at a rate of  $10^7$  tonnes/year.

To produce an amount of energy equivalent to that for America for a year requires 20 tons of Helium-3. This translates into  $2 \times 10^9$  tonnes of mined regolith and is comparable to the production of 50 coal mines. Present US energy consumption would require about 600 lunar mining machines.

The lunar miner would require maintenance. The larger the machine the larger the maintenance capability would need to be. Ultimately, replacement parts might be produced on the Moon utilizing the native iron and titanium. However, parts production would require a huge infrastructure. Should the miner be assembled on the Earth and shipped to the Moon or should pieces be transported and the assembly occur on the Moon?

The machine might be articulated or a multiple vehicle system might be used. One vehicle could mine and beneficiate the regolith; the second would collect and process the material. A multivehicle approach could alleviate problems of associated with down-time of one component.



## PILOT PLANT/DEMONSTRATION

Prototype plant (1/10th the ultimate size) might run on 1 shift/day, operated from the lunar base, using 6 people.

At an early stage (2010-2020) the technology could be demonstrated. In connection with an oxygen plant producing 1,000 tonnes of O<sub>2</sub>/yr a few kg of Helium-3 would be produced. This would demonstrate the isolation and distillation aspects of the procedure as well as the transportation to Earth.

## HELIUM-3 ABUNDANCE

Depth distribution of helium is constrained by only a few cores (Apollo) which extended to a depth of approximately 3m. The helium/argon ratio is constant with depth suggesting that helium, which is much more mobile than argon, has not diffused out of the regolith. There may be no depth dependence within the regolith in the helium abundance and therefore the entire regolith might be minable. Helium might also be cold trapped at depth in the lunar regolith. The temperature reaches a minimum of -50 °C at a depth of about 70 cm (below the diurnal wave). Depending on how the helium is bound to the regolith, mining at night may preserve additional helium that might be lost during daylight mining.

The highlands probably will not provide good candidate sites for helium mining. Anorthite is a very leaky mineral so little helium is retained. The question of cold trapped helium at depth in the highlands regolith remains.

A major question which remains is why ilmenite is such a good helium carrier. Ilmenite is very resistant to radiation damage, unlike other minerals. There may be molecular properties associated with the mineral which enhances its ability to retain helium.

The question of remote detection of helium was discussed. Helium might be detected remotely through two methods. Helium is associated with TiO<sub>2</sub> and the titanium can be detected remotely. Helium content also correlates with regolith maturity and soil maturity can be detected remotely. There is a 0.9µm absorption band due to Fe in pyroxene. As the soil matures, agglutinates form and the absorption disappears.

## PROCESSING

A suggestion was made that it might be easier to separate the helium isotopes on Earth rather than on the Moon. The Earth's higher gravity might help. This cost of processing on the Moon versus that of the Earth bears on this problem.

Where is the material processed. on the miner or at a central plant. The concept of processing on the miners (ultimately as many as 600 in number) requires a similar multiplication of processing plants. It may be more efficient to process the material at a central site. The material could be transported from the mine site(s) to the plant using either conveyor belts or slurry pipelines. If the material is processed at a remote site, the regolith must

be disposed of. Large craters could be used as disposal sites. The remote processing site could be semi-mobile in the sense that periodically, every 5 years or so, it is moved to a more convenient location.

The laboratory studies on the release of helium from regolith are based on step-heating. A question remains about the amount of helium that would be liberated from a short period (seconds) of heating to 700 °C. This question needs to be addressed experimentally.

The concept of heating the regolith in place rather than picking it up was discussed. In-situ heating of the regolith at depth is problematic, and constraining the liberated gas is also difficult. The process of in-situ heating does not recover any energy whereas significant energy is recovered in the miner. Another aspect discussed was whether the regolith really needed to be culled to <50  $\mu\text{m}$  or whether a larger size might not be sufficient.

Alternative processes were suggested to replace the thermal heating of the regolith to release the gas. These other methodologies include acoustic vibration, agitation, grinding, microwave heating.

## IMPLICATIONS

The mining operation may produce a residual atmosphere. The heated regolith which is redeposited on the surface may continue to outgas resulting in a localized, residual atmosphere. Loss of gas from the processing may also result in an increase in the lunar atmosphere. The present lunar atmosphere is on the order of 5,000 kg (total). If gas were released at a rate of 60 kg/sec, a long lived atmosphere could develop.

What do you do with the mining site when you're done mining? If the miner just backfills as it goes, there really is nothing much that can be done with the site. If the material is taken somewhere else for processing, then pits remain. These pits could be converted into radiotelescope sites, landing sites, habitat locations, etc.

## ECONOMICS

If the target price of Helium-3 on the earth is \$1x10E9/tonne, that translates into a cost limit of \$6/tonne to mine a tonne of regolith, extract and process the helium, and ship it to the Earth. If the cost is higher, the process is not profitable. The lower the cost the more profitable. A standard 50% return would require the cost to be \$3/tonne.

A detailed parametric cost analysis is required to determine if Helium-3 mining and production is economical. Specifically, the various strategies for mining and processing need to be addressed as well as whether there should be an instantaneous or gradual build up. The economics of this activity need to be addressed in a global context.

Some of the questions to be addressed include: Can Helium-3 be mined on the Moon and returned to Earth? What are the costs involved in an isolated Helium-3 mining effort? And, what are the cost impacts of doing Helium-3 mining in the context of a lunar base, and to what extent will the other volatiles produced by Helium-3 mining offset those costs.



Who would pay for this and how are investors attracted? Precursors may need to be flown and surface work done to convince investors that the He-3 is there in sufficient abundance and is easily retrieved in order for them to invest. The question of who would invest remains. Would this be a government project, an international project or a private project?

#### QUESTIONS TO BE ADDRESS BY WORKING GROUP I

I-1. What is necessary to validate the feasibility and practicality of D/He-3 fusion and He-3 breeding of Tritium?

I.2. How does D/He-3 compare to the D-T fuel cycle?

- (a) physics requirements
- (b) radiation safety
- (c) waste removal and storage
- (d) power generation
- (e) timeframe to principle demonstration and commercialization
- (f) cost

I.3. How does He-3 compare to Lithium as a blanket material in D.T fusion?

- (a) radiation safety
- (b) waste removal and storage
- (c) cost

#### QUESTIONS TO BE ADDRESSED BY WORKING GROUP II

II.1. How much He-3 is there on the moon and where is it?

- (a) What are the theoretical projections of He-3 supply and the most likely candidate sites for mining?
- (b) What is the minimum concentration of He-3 in the lunar surface for economical mining?

II.2. How do we recover the He-3?

- (a) In what ways can the techniques proposed for mining Lunar oxygen be adapted for He-3 recovery and evolution?
- (b) What power would be required for Helium-3 evolution from the lunar soil?
- (c) What is the order of magnitude of cost to mine He-3 on the Moon?

### II.3. How do we transport the He-3 to Earth?

- (a) What processes would be required to liquify and store the Helium-3 after recovery?
- (b) What infrastructure and transportation capabilities must be in place before lunar mining can be reasonably initiated?
- (c) What is the order of magnitude of cost to transport He-3 to Earth?

### QUESTIONS TO BE ADDRESSED BY PLENARY SESSION (Day 2)

P.1. Are there ramifications (legal, environmental, political, scientific, economic) to mining He-3 from the moon? Are there additional ramifications in using He-3 on Earth?

P.2. If a viable and practical method for obtaining He-3 from the Lunar surface could be made available, what impact would this have on the fusion community, the United States, and the world?

P.3. Are there important questions or factors that have not been addressed by this workshop?

### QUESTIONS TO BE ADDRESSED BY WORKING GROUP II

#### Questions:

1. How much Helium-3 is there on the Moon and where is it?

Helium shows a high correlation with the content of  $TiO_2$ ; the greater that  $TiO_2$  content, the greater the helium concentration. Average concentrations of helium in lunar mare regolith are about 30-40 ppm; it varies from zero to about 300 ppm (He-3 concentrations are  $9 \times 10^{-3}$  ppm). At least observationally, the helium is preferentially found in the basaltic regolith of the lunar maria. Helium-3 is found in the highlands regolith, but anorthosite is extremely porous to such elements and the implanted helium rapidly diffuses away. Helium is concentrated in the <50 micron-size-fraction of lunar regolith.

Helium probably can not be detected directly from orbit. The close association between it and  $TiO_2$ , however, allows secondary detection. High-titania basalts are easily mapped using multispectral imaging systems from orbit. More mature (older) regolith, containing larger quantities of He-3, can also be mapped from orbit on the basis of their spectral characteristics. Apollo data provides excellent data base for front-side low-latitude. The Lunar Geosciences Observer will provide a global high resolution data base as it will be in a polar orbit.

- 1a. What are the theoretical predictions of Helium-3 supply and the most likely candidate sites for mining?

From the existing data base, the average concentration is likely to be about 30-40 ppm of Helium in the mare ( $9 \times 10^{-3}$  ppm He-3). There may be areas of higher concentrations as well as lower ones. The best candidate site (Based on present knowledge) on a regional basis is Mare Tranquillitatus; second choice is Mare Procellarum.

1b. What is the minimum concentration of Helium-3 in the lunar surface for economic mining?

The average helium concentration of 30-40 ppm is probably commercially viable, higher concentrations would clearly be viable. The exact lower limit is a more subjective assessment. The panel felt that about 5-10 ppm was probably a practical lower limit based on recovery technology. An economic lower limit was not defined but would be the concentration needed to break even. Bypassing material would only be done if the cost of bypassing it were greater than just sending it through the system. This limit could only be determined once a detailed economic analysis was completed.

## 2. How do we recover Helium-3?

There are two aspects to this question; the physical collection of material and its processing from a mechanical standpoint, and the actual extraction and collection of Helium-3.

Collection of the material was envisioned to be done using a lunar miner. This device would move across the lunar maria collecting material down to a depth of 3 meters. The proposal suggested an initial screening to remove material  $>4$  mm. This culled material was then electrostatically sorted to remove material  $>50$  microns. It was this final  $<50$  micron fraction that would be used in the generation of volatiles, including volatiles.

The miner operates at a rate of 1,258 tonnes/hour and for 3,942 hours/year (daylight). It excavates a path 3m deep and 11 wide and covers about 1 sq km/year (an area visible telescopically). Total yearly tonnage is  $5 \times 10^6$  tonnes to produce 33kg of Helium-3.

The  $<50$  micron fraction is then passed into a heater which elevates the material to a temperature of 1,000K (750 °C). The heating process yields not only helium but also a suite of other volatiles (e.g., water,  $N_2$ , CO,  $CH_4$ ,  $CO_2$ , and  $H_2$ ). The volatiles are recovered by a condensation process.

Alternatives to heating the fines to drive off the volatile include acoustic vibration, grinding, agitation, microwave heating. These technologies need to be explored, with the goal of reducing operating cost. The use of an electrostatic separator for concentrating fines may not be the most effective, and trade studies and experiments should be conducted to evaluate the most effective concentration techniques. Further analyses are necessary to optimize the extent to which material extraction is fully mobile, partly mobile, or fixed.

The  $H_2$  is removed before cooling/condensation and then the remainder is cooled to 55 K. The derived Helium is then subjected to cryogenerator which liquifies the two isotopes for separation by a superleak. This cryogenic cryo-distillation method can reach 99% efficiency.

2a. In what ways can the techniques proposed for mining lunar oxygen be adapted for Helium-3 recovery and evolution?

The specific chemical technique for oxygen production can not be adapted to helium recovery ( $\text{FeTiO}_3 + \text{H}_2 \rightleftharpoons \text{Fe} + \text{TiO}_2 \rightleftharpoons \text{H}_2 + \text{O}$ ). However, the techniques for collection of regolith used in the oxygen production operation can be quite easily used for the Helium-3 production.

The process used in the extraction of Helium-3 apparently produces  $\text{H}_2\text{O}$  as one in a suite of volatiles. Enough of this may be produced to augment or replace the oxygen obtained from the lunar oxygen production system. The abundance of  $\text{H}_2\text{O}$  in representative extractions needs confirmation.

2b. What power would be required for Helium-3 evolution from the lunar soil?

The total power required to develop the infrastructure on the Moon, mine the regolith, isolate the Helium-3 and return it to Earth is, as estimated by the Wisconsin group, to be about 2253 GJ/kg He-3. This value is composed of Transportation of Equipment @ 1983 GJ/kg; Gas Separation @ 186 GJ/kg; Mobile Miner (Ops) @ 84 GJ/kg. If the costs of the development of a fusion plant on Earth to use the Helium-3 are included, then the cost escalates to about 7300 GJ/kg He-3.

The power source for the miner could be either solar or nuclear. Both power sources have their advantages and disadvantages. Solar would allow only daylight operations but be technically simple; nuclear would allow night operations as well as day but be technically more difficult in that nuclear energy would have to be efficiently converted to thermal energy.

2c. What is the order of magnitude of cost to mine He-3 on the Moon?

This question is extremely difficult to answer at the present time. It requires a detailed parametric engineering cost analysis to estimate. However, at a target price of \$1G/metric tonne of Helium-3 on Earth, the mining cost translates to about \$6/tonne. Another number is \$444/GJ expended energy.

The total operational cost of producing Helium-3 may be offset by the savings derived from in-situ production of life support volatiles and significant amounts of propulsive fuels (H and O). These by-products of helium mining occur in quantities well above that which can be used in a lunar base, hence they may also be exportable to space stations in earth orbit (LEO/GEO).

3. How do we transport the Helium-3 to Earth?

Two options were discussed with regard to this process; separate the helium isotopes on the Moon and transport the Helium-3 to earth or transport all of the helium to earth and separate the isotopes on the ground. It was felt that the difficulty of controlling the final isotopic separation might be such that processing on Earth would be required. Further trade studies are necessary.



3a. What processes would be required to liquify and store the Helium-3 after recovery?

Specifically, the volatiles evolved from the regolith are collected. These gases are then cooled and condensed. The helium is then isotopically separated into helium 3 and 4. Hydrogen is first removed by diffusion. The remaining gases are then cooled in a condenser to separate out the different volatiles as they condense. The remaining helium gas is then cooled to 1.5-2.2K to enrich the He-3 by a factor of about  $10E-4$ - $10E-2$  in a superleak separator. Next a cryogenic distiller is used at a temperature of 2.3 - 4.2K to enrich the He-3 to 99%.

3b. What infrastructure and transportation capabilities must be in place before lunar mining can be reasonably initiated?

A pilot plant to test the concepts of the process and demonstrate its ability to function in the lunar environment can probably be run concurrently with the early phases of the lunar base. A more involved test bed can operate during the oxygen production facility operation. Finally, a helium production facility would replace all other volatile-specific operations because all volatiles are by-products of the helium collection/condensation process.

The full scale helium production facility would require a fleet of miners, gas storage and transfer vehicles, support facilities, maintenance facilities, launch and recovery facilities.

3c. What is the order of magnitude of cost to transport Helium-3 to Earth?

Again, similar to question 2c, the dollar costs are difficult to assess without a detailed economic analysis and because the availability of technology in the 2010-2015 time frame is unknown. From an energy perspective, the cost of returning Helium-3 to the Earth is relatively small.



DISCUSSION ON THE REPORT OF THE  
LUNAR MINING WORKING GROUP

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Some of the following discussion was incorporated into the rapporteur's report.

Resource

Regolith is primarily a very fine dust. Ninety-nine percent is less than four millimeters in diameter. Forty five percent is less than fifty micrometers. The surface area to mass ratio is one half square meter per gram.

Stirring is the accepted explanation for the relatively uniform depth distribution of solar wind gas atoms in the regolith. Laboratory experiments support this. Large lunar rocks show no solar wind gas in their interiors (except for brechia, which is large rock aggregated from many smaller pieces).

The correlation between He atom concentration and ilmenite abundance is not understood fundamentally. However, there is a good correlation between soil maturity (age) and percent He which supports the "stirring" hypothesis.

There is an incident He flux onto the lunar disk of eight grams per second. The  $^3\text{He}$  flux is approximately one two-thousandth of this. This is the renewal rate!

Many mining operations on earth move millions of tonnes per year. Lunar  $^3\text{He}$  mining would be an operation of similar size. Boulders, on and under the surface, would be a hazard for large bucket-type mining equipment. Planning a path around boulders or removing them will be required.

Products

Several other gases are released (as mentioned in the rapporteur's report) during the recovery of  $^3\text{He}$ . One of these is hydrogen. The processing could be designed to also release oxygen from ilmenite, and a product of this reaction would be quantities of water.

A process designed to extract oxygen from ilmenite would only release about fifteen percent of the helium, because oxygen is found in

the volume and helium on the surface of ilmenite. Thus, an oxygen focussed process would throw away the fine grained helium-rich soil.

A small pilot plant could be operated on earth if the very small sample of returned lunar material were available and adequate, otherwise pilot plant operations would be on the moon.

### Energy

The University of Wisconsin group estimated that 2253 GJ would be expended per kilogram of  $^3\text{He}$  returned to earth. This energy was only for transportation to the moon. All other energy expenses were judged to be small. Discussion brought out that 12 MW must be expended continuously during sunlight hours to produce 33 kilograms per year of  $^3\text{He}$ .

U. Wisc. researchers have looked into various sources of energy for processing regolith. Because it couples well with titanium oxides, microwave energy was considered, but later rejected because, in comparison to thermal processes which permit energy recovery, microwaves are energy inefficient. Solar thermal power, which is "free", was chosen for the early U.Wisc. miner/processor design.

Another suggestion for supplementing energy requirements was to employ lunar hydrogen and oxygen in a fuel cell. While recognizing that this approach would not generate enough energy to run the entire process continuously, it provides a mobile energy source and releases chemical energy in a useful form.

### Cost

Cost estimation was the weakest area to be addressed.

### Issues

*How confident are we about the correlation between ilmenite and helium?* A distinction was made between scientific confidence and the level of confidence on which to base a commercial operation. There appears to be enough data to establish that there is a correlation, however the full set of characteristics, necessary for a commercial decision, have not been established. Additional data on the aerial distribution of ilmenite and of mature soil could be obtained from a Lunar Science Orbiter, with spectroscopic instruments

*How much  $^3\text{He}$ , being transported for commercial fusion power, could we afford to lose in a single accident or interruption?* The size of return loads may have to be limited. Insurance may be a big question. Several independent-suppliers could be the option to provide a continuous supply.

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THE MOON: AN ABUNDANT SOURCE OF CLEAN AND SAFE  
FUSION FUEL FOR THE 21st CENTURY\*

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\*Presented at the 11th International Scientific Forum on Fueling the 21st Century, September 29 - October 6, 1987, Moscow, USSR.



## 1) INTRODUCTION

Modern societies depend on energy for their very existence. Without it, the earth cannot support its present population of 5 billion people let alone even dream about supporting the 8 to 10 billion people that are likely to inhabit the earth under the so called "equilibrium" conditions<sup>(1)</sup> in the 21st century. We have long passed the time when most humans can "live off the land". At the present time, the average primary energy consumption is slightly over 2 kW per capita,<sup>(2,3)</sup> but over 70% of the world's population is well below that average and is desperately trying to improve its standard of living. Therefore, copious amounts of energy will be needed over the next century to feed, clothe, warm, cool, protect and keep the earth's citizens healthy in the face of an environment under increasing stress.

Ever since the world population passed the 1 billion mark in 1830, fossil fuels such as coal, oil and natural gas have been used to sustain life on this planet. Up through 1986, we have used approximately 300 TW-years of that energy (1 TW-y =  $10^{12}$  watts for one year). Our present world population of 5 billion people (up from 2 billion in 1930, 3 billion in 1960, and 4 billion in 1975) and a usage rate of ~2 kW/capita, means that we are currently using primary energy at a rate of ~10 TW-y/y. As we move toward the "equilibrium" world population of 8 to 10 billion people, and allowing for some modest increase in the standard of living for the underdeveloped nations, our future worldwide primary energy consumption rate will be between 20 and 30 TW-y/y. Since we have only 1000-1500 TW-years of fossil fuel energy left that is economically recoverable,<sup>(2,3)</sup> it is easy to see that somewhere in the mid 21st century we will exhaust our fossil fuel resources. It is also possible that environmental problems such as acid rain, the CO<sub>2</sub> "greenhouse" effect, or wars over the last remaining deposits of fossil fuels will limit the useful lifetime to even less than that determined by resources alone. It is also important to note that fossil fuels will also be of increasingly greater value as chemical feedstocks for non-fuel products to sustain the quality of life. In any case, for much of the 21st century, inhabitants of the earth will have to rely on renewable energy sources (solar, wind, hydro, geothermal, and biomass) and nuclear energy sources to survive.

The use of nuclear energy in the form of fission reactors is already widespread with some 370 reactors located in 26 countries which provide approximately 1/6 of the world's electricity. By the year 2000, this fraction will increase to approximately 1/5. However, this source of energy is not without its problems which currently range from public resistance to the storage of long lived fuel cycle wastes to reactor safety questions.

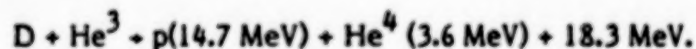
Fortunately, there is another form of nuclear energy which could provide an even more environmentally acceptable and safer solution to our long range energy problems. The fusion of certain light elements into heavier ones at high temperatures can release enormous amounts of energy. This is evident every day as we observe the fusion energy released by our sun, and every night as we observe the billions upon billions of stars which themselves are powered by fusion reactions.

Scientists have been trying to reproduce a controlled fusion reaction here on earth since 1951. After 36 years of research and the expenditure of over 20 billion dollars in a worldwide program, we are now within a year or two of the first "breakeven" experiments, historically similar in some ways to the Chicago Stagg Field fission reactor experiment conducted by Enrico Fermi and his colleagues in 1941.<sup>(4)</sup> Before the end of this decade, magnetically confined plasmas in the TFTR device at Princeton, USA<sup>(5)</sup> and/or the JET device in Culham, UK<sup>(6)</sup> will release more thermonuclear energy than required to initiate the fusion reaction.

Scientists have already anticipated success in these devices and have designed the next generation of fusion devices which will produce 100's of megawatts of thermonuclear power in the 1990's.<sup>(7)</sup> Work has even begun on commercial fusion power plants<sup>(8,9)</sup> and for fusion power sources in space.<sup>(10)</sup>

Currently, the worldwide effort in fusion is concentrating on the deuterium (D) and tritium (T) reaction because it is the easiest to initiate. However, 80% of the energy released in this reaction is in the form of neutrons and these particles not only cause severe damage to the surrounding reactor components, but they also induce very large amounts of radioactivity in the reactor structure.

It is fortunate that there is another fusion reaction, involving the isotopes of deuterium and helium-3 ( $\text{He}^3$ ) which, in theory, involves no neutrons or radioactive species, i.e.,



Unfortunately, some side DD reactions do produce neutrons and roughly 1% of the energy released in this reaction is released in the form of neutrons. However, such a low neutron production (compared to the DT cycle) greatly simplifies the safety related design features of the reactor and induces such low levels of radioactivity that the wastes do not require the extensive radioactive waste facilities that are so unpopular with the public today. Furthermore, since over 99% of the energy can be released in the form of charged particles, this energy can be converted directly to electricity via

electrostatic means (similar to running a charged particle accelerator backwards) with efficiencies of 70-80%.

If this reaction is so advantageous, why haven't we been pursuing it more vigorously in the past? The simple answer to that is that there is no large terrestrial supply of  $\text{He}^3$ ! The amount of primordial  $\text{He}^3$  left in the earth is on the order of a few 100 kg's<sup>(11)</sup> and the  $\text{He}^3$  which results from the decay of manmade tritium ( $t_{1/2} = 12.3$  years) is also only being produced at a rate of 10-20 kg/year. Since the energy equivalent of  $\text{He}^3$  is 19 MW-y per kg, one can see that to provide a significant fraction of the world's energy needs would require 100's of tonnes of  $\text{He}^3$  per year, not 100's of kg's per year.

What is the solution? In 1986, it was pointed out by scientists at the University of Wisconsin<sup>(11)</sup> that over the 4 billion year history of the moon, some 500 million metric tonnes of  $\text{He}^3$  hit the surface of the moon from the solar wind. The analysis of Apollo and Luna retrieved samples showed that over 1,000,000 tonnes of  $\text{He}^3$  still remain loosely-imbedded in the surface of the moon. The object of this paper is to show how that  $\text{He}^3$  can be obtained from the moon and how its use in fusion reactors can benefit the inhabitants of this planet. We will begin, in reverse order, by addressing the physics and technology issues associated with the use of  $\text{He}^3$  and finish with a description of its distribution on the moon and of methods which could be used to retrieve it.

## II) THE PHYSICS OF THE D- $\text{He}^3$ FUSION REACTION

When certain light isotopes are heated to extremely high temperature and confined to a small region of space, they can react with each other producing a heavier atom which weighs less than the reactants. The missing mass is converted into energy. The reaction rate of selected fusion fuels is plotted in Figure II-1 and reveals that the DT reaction occurs at the lowest temperatures. Figure II-1 also shows that as the temperatures are increased above 10 keV (1 keV is roughly equivalent to 10,000,000°K) the DD, then the D- $\text{He}^3$  reactions, become significant. For various physics reasons, the optimum temperature at which to run these reactions ranges from 10-20 keV for the DT reaction to 50-60 keV for the D- $\text{He}^3$  plasmas.

It was pointed out earlier that the presence of deuterium atoms in a D- $\text{He}^3$  plasma can result in DD reactions as well as D- $\text{He}^3$  fusions. These reactions are listed below (each occurs with roughly equal probability)

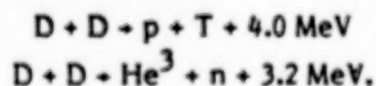
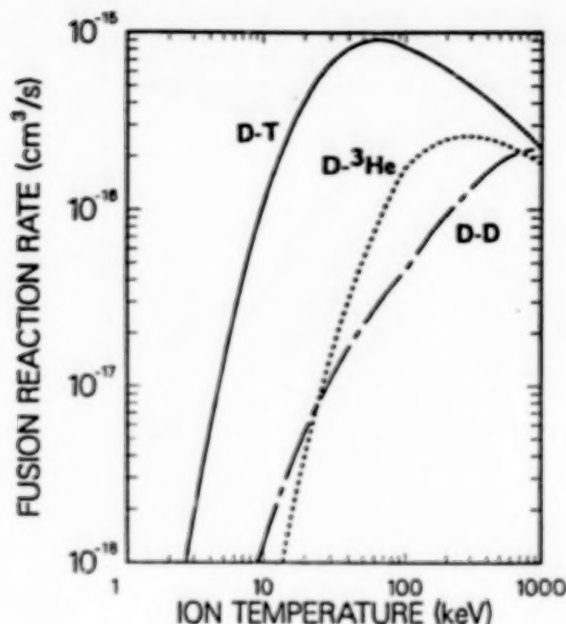


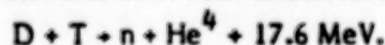


Figure II-1

## MAJOR FUSION FUEL REACTIVITIES



Not only does one of the DD branches produce a neutron but some of the tritium produced by the other branch can also burn with deuterium by the following reaction



The ratio of power released in the form of neutrons compared to that released in the D-He<sup>3</sup> fusion is then given as

$$\frac{P_n}{P_{D-He^3}} = (\text{Constant}) \left( \frac{n_d}{n_{He^3}} \right) \left( \frac{\langle \sigma v \rangle_{dd}}{\langle \sigma v \rangle_{dHe^3}} \right)$$

where

$n_d, n_{He^3}$  = number densities of deuterium and He<sup>3</sup>, respectively

$\langle \sigma v \rangle_{dd}$  = fusion reaction rate of deuterium ions

$\langle \sigma v \rangle_{dHe^3}$  = fusion reaction rate of deuterium ions and He<sup>3</sup> ions

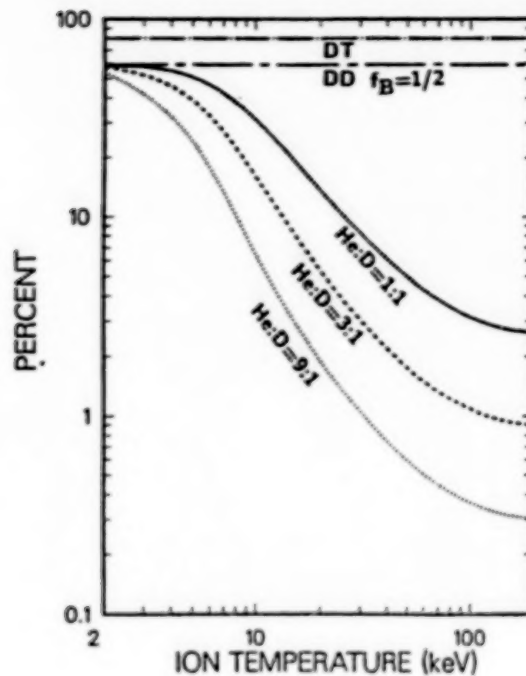
Constant = 0.03 if none of T<sub>2</sub> is burned and = 0.18 if all the T<sub>2</sub> is burned (at 60 keV).

It can be seen that there are two main factors which can cause the power in neutrons to be reduced; operation at temperatures where the ratio of the reaction cross sections is minimized and increasing the helium-3 to deuterium ratio. This latter parameter cannot be pushed too far because eventually there would not be enough deuterium atoms available for fusion and the fusion power density would be too low.



Figure II-2

# PERCENT OF FUSION POWER IN NEUTRONS (50% Tritium Burnup)



One example of how these two parameters can affect the power released in neutrons is shown in Figure II-2. Here it is shown that 80% of the fusion power released in the DT reaction is in the form of neutrons. The neutron fraction is 50% for the DD reaction and, depending on the temperature and He<sup>3</sup> to D ratio, as little as 1% of the energy could be released in neutrons from D-He<sup>3</sup> plasmas.

Aside from the advantages of low neutron production, which will be covered later, the fact that 99% or so of the energy from this reaction is released in energetic charged particles also is of major significance. These particles can be converted to electricity via direct electrostatic means. Workers at LLNL in the U.S. have shown that this can be accomplished with 70-80% efficiency at lower energies.<sup>(12)</sup> There is no reason to expect the higher energy (MeV) ions will substantially change those results.

Another advantage of this reaction is that it can be tailored to release large amounts of synchrotron radiation. Logan<sup>(13)</sup> has shown over half the energy from a D-He<sup>3</sup> plasma in a tokamak can be released in microwaves at 3000 GHz (~0.1 mm wavelength). Such energy could be removed from the plasma chambers via waveguides and directed to useful areas outside the reactor. Direct conversion of the microwaves to

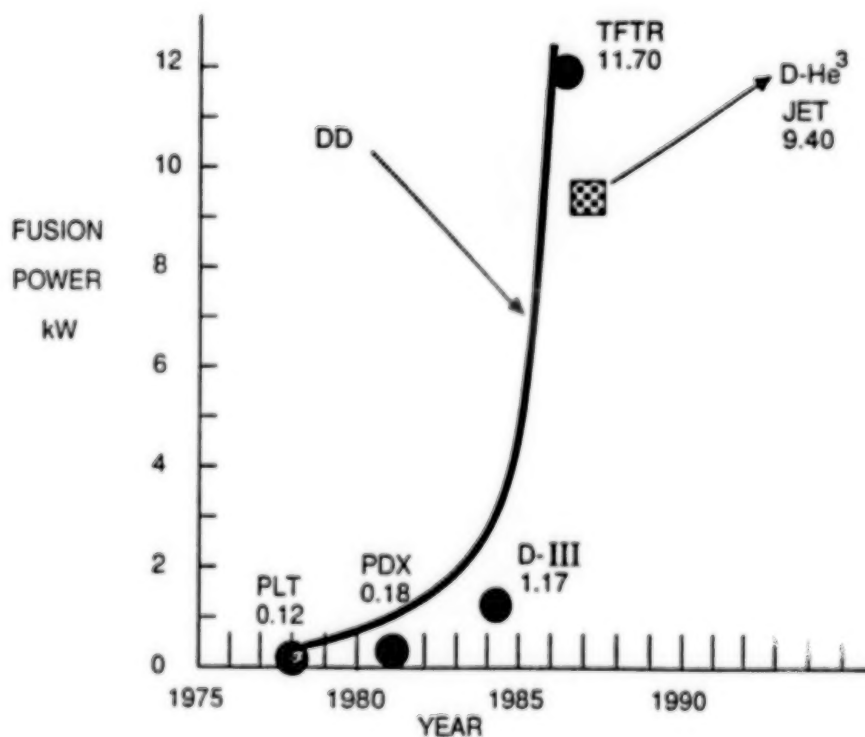
electricity via rectenna could also improve the performance of the power plant. Other uses of the microwaves such as propagating energy over long distances in space or for local uses in the vacuum of space are also being investigated.

Coming back to Figures II-1 and II-2, it is evident that D-He<sup>3</sup> plasmas will have to be operated at temperatures about 3 times higher than DT power plants. Experiments at TFTR<sup>(14)</sup> have already achieved temperatures equivalent to -20 keV and methods to get to 60 keV ion temperatures in tokamaks have already been discussed for NET, the Next European Torus.<sup>(15)</sup> Considering that in the past 2 decades, we have increased the plasma temperatures in tokamaks by over a factor of 100 from 0.1 keV to 20 keV, it is not unreasonable to expect another factor of 3 increase in the next decade.

It is also of interest to note that when we examine the actual amount of thermonuclear power that has been produced in the laboratory, we find that the situation is quite favorable for D-He<sup>3</sup>. Figure II-3 shows the power released from DD plasmas in magnetically confined devices (no DT plasmas of any significance have been operated to date). It can be seen that starting with PLT in 1981 and progressing to TFTR in 1986 the fusion power released in the laboratory has increased to the level of 12 kW for a few seconds.<sup>(16)</sup> Recent experiments by Jacquinot<sup>(17)</sup> at JET in 1987 have released over

Figure II-3

### THERMONUCLEAR FUSION POWER PRODUCED



9 kW from D-He<sup>3</sup> reactions. It is anticipated that this energy release will approach 1 MW when all of the heating is installed on JET in 1988.

How will the breakeven and ignition experiments for D-He<sup>3</sup> be conducted? Emmert et al.<sup>(15,18)</sup> have shown that for the present European design of NET, simply inserting a D-He<sup>3</sup> plasma in place of the reference DT plasma will produce breakeven conditions. In fact, the energy multiplication can actually approach 2.5 if the inboard DT neutron shield is replaced with a thinner D-He<sup>3</sup> neutron shield (because of the lower neutron production less material is needed to shield the magnets from radiation damage). Such a modification is easily done when the machine is constructed and then the shield can be replaced before DT operation commences.

An even more interesting result was obtained by Emmert et al. when they examined a combination of thinner inboard shields and a 20% higher magnetic field on TF coils. It was found that NET could actually ignite a D-He<sup>3</sup> plasma in this case and that significant power production (100 MW) could be achieved. Such modifications could be made for less than a 10% cost impact on the design and would allow scientists to study ignited D-He<sup>3</sup> plasmas in the 1998-2000 time period (assuming the current 1992 construction date is maintained). This is less than 5 years after we expect to reach ignited conditions in a DT plasma in CIT.<sup>(19)</sup> It is therefore quite possible that we could enter the 21st century with ignited plasmas containing both D-He<sup>3</sup> and DT fuel!

In summary, the physics of the D-He<sup>3</sup> reaction is well established and in fact, it is being studied in the major tokamaks of the world today. One of the current reasons to study this reaction is to learn about the slowing down of fast ions in hot plasmas without activating the machine significantly with neutrons. This latter point is also one of the main reasons we are interested in this fuel cycle from a commercial standpoint.

### III) TECHNOLOGICAL ADVANTAGES OF THE D-He<sup>3</sup> FUEL CYCLE

Assuming that we can produce a well-controlled, sustainable D-He<sup>3</sup> fusion plasma, what technological advantages does it have over the DT cycle? We can identify at least 6 major features, most of which stem from the much lower neutron production:

- 1) Reduced radioactivity
- 2) Reduced radiation damage
- 3) Increased safety
- 4) Increased efficiency
- 5) Lower cost of electricity
- 6) Potentially shorter path to commercialization

Let us briefly examine each of these points.

#### III.A) Reduced Radioactivity

It stands to reason that if we produce less neutrons per unit of power, then the amount of radioactive structural material will be reduced. Attaya et al.<sup>(20)</sup> have

Table III-1

A Comparison of the Waste Disposal Characteristics of Similar Structural Materials Used in DT and D-He<sup>3</sup> Fusion Reactor Designs

	Component Lifetime	DT Fuel Cycle $r=2.55 \text{ MW/m}^2$	D-He <sup>3</sup> Fuel Cycle $r=0.05 \text{ MW/m}^2$
PCA (An Austenitic Stainless Steel)	Blanket 2 y	Class C	Class A
	Shield 30 y	Deep Geologic Waste Repository	Class C
HT-9 (A Ferritic Stainless Steel)	Blanket 2 y	Class C	Class A
	Shield 30 y	Class C	Class A

#### Form of Waste

Class A - Can be buried in shallow trench and no special requirements on stability of container. Waste may be unstable.

Class C - Buried at least 5 meters from surface and in chemically and structurally stable container for 500 years.

Deep Geologic Waste Repository - Must be sequestered from public and the environment, at least 200 meters below surface, usually for periods exceeding several 1000 years and continuously monitored. Details considered on case by case.

examined the activation induced in materials that might be used in the Ra<sup>(21)</sup> D-He<sup>3</sup> reactor design and compared it to the activation that would be in the same materials used in the DT powered MiniMars reactor <sup>(22)</sup>. A summary of their results is given in Table III-1. It was found that not only were the radioactivity levels reduced, but that the material could qualify as class A waste burial material when the plant was torn down. This means that instead of having to bury the reactor components in a deep geologic repository (perhaps as much as a mile below the surface), they could be disposed of in trenches near (within 1 meter) the surface. The shorter half life and stability of the D-He<sup>3</sup> produced wastes should greatly reduce decommissioning costs and alleviate the fears of the public about sequestering the wastes for thousands of years, as is currently the case for fission wastes. Furthermore, the volume of wastes is greatly reduced because of the reduced radiation damage; the amount of "high level" wastes produced by a D-He<sup>3</sup> fusion plant per 1000 MWe-y (enough electricity for a city of a million people for one year) would fit within a single oil barrel. This is in contrast to a volume of over



60 barrels for a similarly powered DT plant and orders of magnitude less than from a fission power plant and its reprocessing facility.

### III-B) Reduced Radiation Damage

If we again use the Ra<sup>(21)</sup> and MiniMars<sup>(22)</sup> reactor designs as reference points we find that after 30 FPY's (full power years), the total DT damage to the first wall is over 1100 dpa (displacements per atom). One dpa means that every atom is displaced once during the component's lifetime and 1100 dpa means that every atom is displaced 1100 times! We do not yet know how to make materials last for much over 100 dpa in fission reactors so the entire inner structure of the MiniMars reactor must be replaced at least 10 times during the reactor lifetime. This causes loss of availability (higher electricity costs) as well as a larger volume of radioactive waste.

On the other hand, we find that in order to produce the same amount of electrical power, the components of the D-He<sup>3</sup> Ra<sup>(21)</sup> reactor only suffer less than 50 dpa. Furthermore, since there is no need to run the blanket at very high temperatures to produce electricity efficiently, the operating temperature can be lower, thus expanding our choice of materials and confidence that they will last the life of the plant. Figure III-1 displays the dpa/temperature parameter space for Ra and MiniMars along with an indication of the current data available on radiation damage to stainless steels. It is clear that the radiation damage from the DT reaction is much larger than anything we have experienced in fission reactors. Contrary to that situation is the fact that both the radiation damage and temperature conditions are much lower for the D-He<sup>3</sup> power plant and it is easy to see why we expect that we can construct a reactor which will last the lifetime of the plant. The much more benign reactor environment should also help in reducing the risk of failures in the reactor and increase our confidence in its safety.

### III-C) Increased Safety

There are at least two different ways to look at this area; from a potential after-heat or meltdown phenomena and from the release of volatile radioactive elements. Sviatoslavsky<sup>(23)</sup> has calculated the consequences of an instantaneous loss of the coolant in the Ra (D-He<sup>3</sup>) reactor on the temperature increase in the surrounding structure. A summary of his results is shown in Figure III-2. It was found that in the absolute worst case of no heat loss during the accident (i.e., as if a perfect thermal insulator was placed around the blanket immediately after losing all cooling water) the maximum temperature increase after one day is -10° C for a D/He<sup>3</sup> ratio of 1:3. After a week it was 50° C and after one month it could have increased by 200° C. It is obvious that a meltdown is

Figure III-1

# **RADIATION DAMAGE IN DHe3 FUSION REACTORS IS MUCH LESS THAN IN DT SYSTEMS**

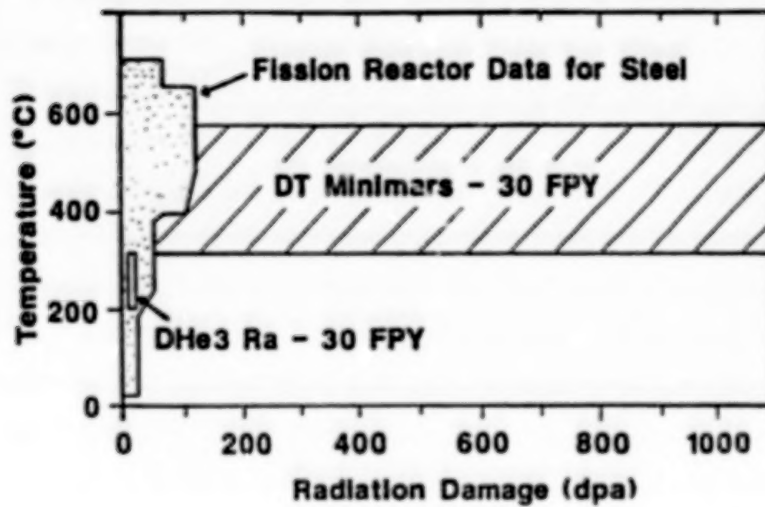
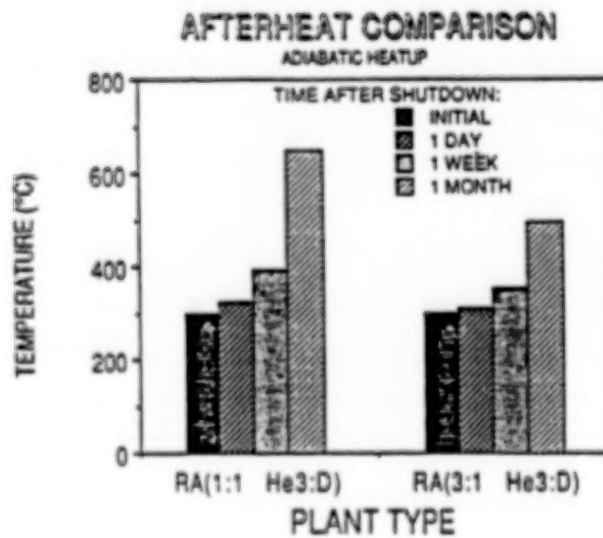


Figure III-2



practically impossible because of the low afterheat levels generated and because there always would be some heat leakage by conduction or convection. Without the possibility of a major thermal excursion in the event of a highly unlikely, but theoretically feasible accident, the safety regulations on such a plant should be eased with a corresponding reduction in construction costs.

The other area of interest is the loss of tritium from a fusion reactor in the event of an accident that could somehow destroy all containment. The worst case, of course, is to release all the tritium in the reactor in the form of tritiated water (HTO) and having the accident occur during the worst meteorological conditions. Assessing such an event for the MiniMars<sup>(22)</sup> plant, Wittenberg<sup>(24)</sup> found that the maximum exposure to a member of the public who lives at the plant boundary would be 24 Rem (coincidentally not far from the exposure that would have been experienced at a similar position to the Chernobyl plant during its accident). Because of the much lower  $T_2$  content in Ra (the tritium comes from one of the DD reactions discussed in section II) the corresponding exposure to the public would be only 0.1 Rem, or roughly equivalent to the annual exposure to the natural background (see Figure III-3). Again, the lack of catastrophic consequences should be reflected in lower costs of construction and hence, lower costs of electricity.

#### III-D) Increased Efficiency

Because the charged particles can be directly converted to electricity with 80% or higher efficiencies, we can generate electricity from D-He<sup>3</sup> fusion reactors at roughly twice the efficiency from fossil or fission power plants (see Figure III-4). The DT and DD systems have only 20 and 50% of their energies released in charged particles and therefore have lower overall efficiencies than for the D-He<sup>3</sup> case but still higher than the thermodynamically limited Light Water Fission Reactors (LWR's) and fossil plants. The higher efficiency can greatly decrease the cost of electricity and have an additional benefit of reducing the size of the heat transport system, the turbine buildings and the waste heat facilities.

#### III-E) Lower Cost of Electricity

It is too early to be able to calculate with any confidence the absolute cost of electricity from any fusion power plant. However, we can compare relative costs of different fusion cycles with some confidence. Using the same costing algorithms from the MiniMars<sup>(22)</sup> study as well as others derived for the U.S. tokamak program, we have compared the Ra device to MiniMars. The results are summarized in Table III-2. We find

Figure III-3

TRITIUM INVENTORY AND MAXIMUM EXPOSURE  
TO PUBLIC IF ALL TRITIUM IS RELEASED

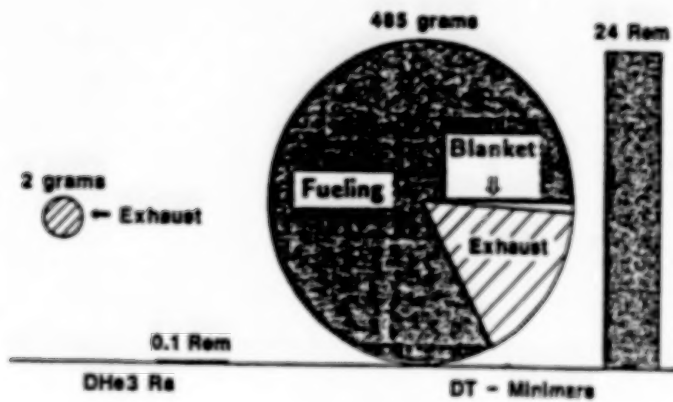


Figure III-4

COMPARISON OF NUCLEAR ENERGY OPTIONS  
THERMAL CONVERSION EFF. %

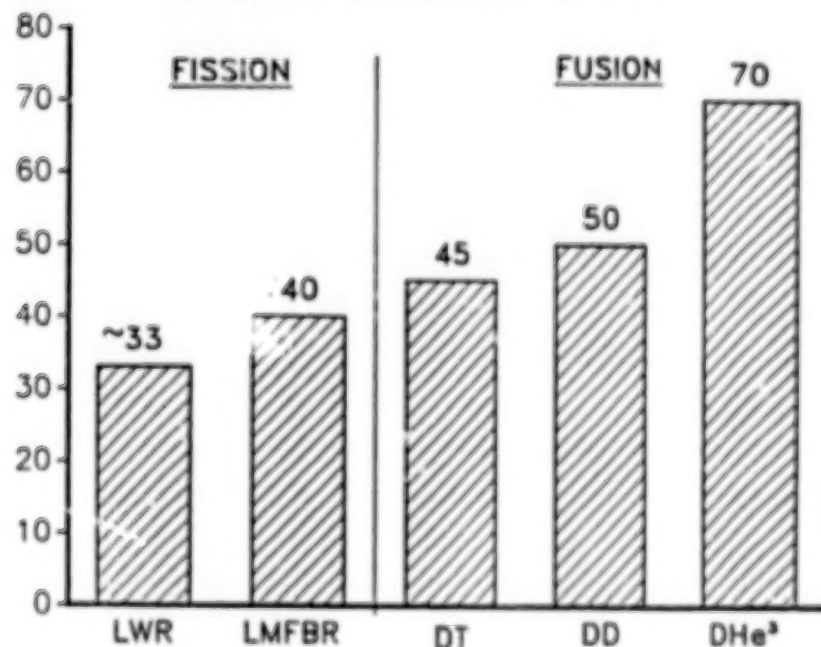




Table III-2

D-He<sup>3</sup> Fusion Reactors Will Have a Considerable  
Cost Advantage over DT Fusion Systems

	DT <u>MiniMars</u>	D-He <sup>3</sup> <u>Ra</u>
Net Power - MW <sub>e</sub>	600	600
Direct Capital Cost \$/kW <sub>e</sub>	1800	1250
Cost of Electricity mills per kWh	42	29*

\*Note - He<sup>3</sup> fuel costs would add 1 mill/kWh per 100\$/g.

a D-He<sup>3</sup> power plant could be as much as 1/3 less than a similar DT plant. The impact of such a lower electricity cost applied to the U.S. alone for 1987 would mean roughly a 30 billion dollars savings to consumers. While the exact numbers can be questioned, that the impact is in the 10's of billions of dollars can not.

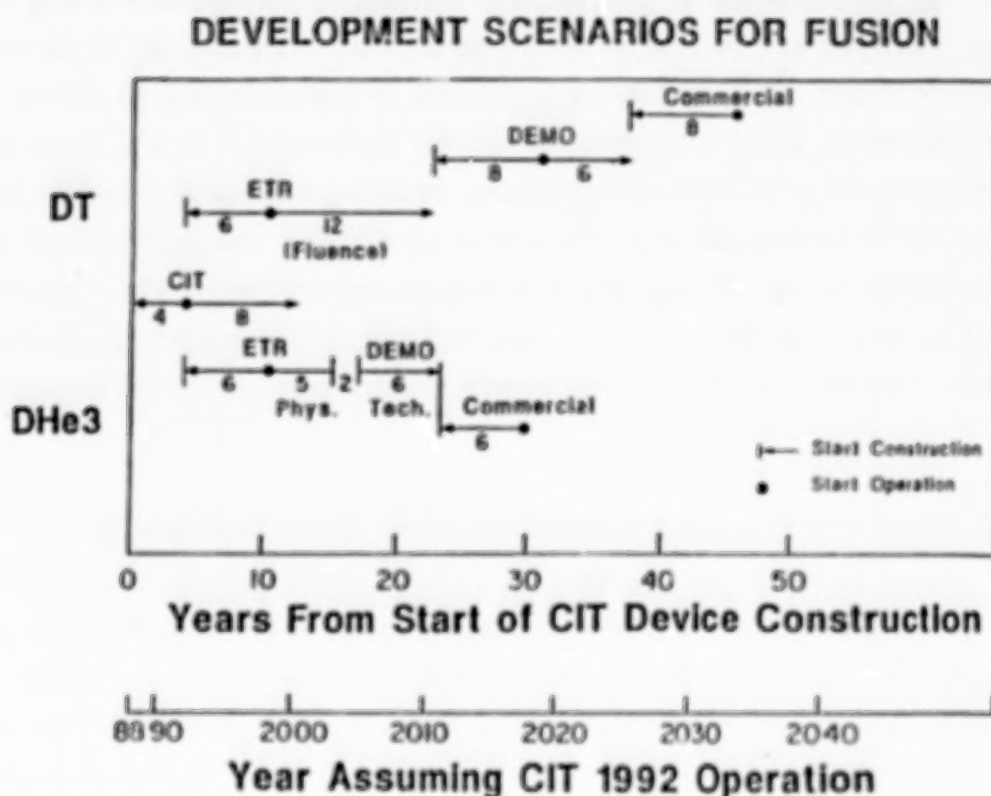
It is also worthwhile to note that at 100 \$/g of He<sup>3</sup> fuel, the cost of electricity would increase by 0.001 \$/kWh. It is felt that one could pay up to 0.01 \$/kWh for the fuel without unduly reducing the attractiveness of the D-He<sup>3</sup> fuel cycle. At 1 billion dollars a tonne, this provides a valuable incentive to study the procurement of this valuable fuel.

#### III-F) Potentially Shorter Path to Commercialization

One of the great advantages of the D-He<sup>3</sup> fuel cycle is the fact that once it can be ignited, the development path to a commercial unit should be much easier than for the DT system. After ignition of a DT plasma is achieved and the understanding of how to control such plasmas is in hand, there remains the long and expensive process of testing materials and breeding concepts for commercial units. Along the way, demonstration power plants would have to be built to integrate the plasma physics and materials physics aspects. The current U.S. approach to that process is shown in Figure III-5.

On the DT side it begins with the CIT<sup>(19)</sup> device scheduled for operation in the early 1990's. The main objective of this device is to demonstrate ignition of DT plasmas, presumably about the middle of the 1990's.

Figure III-5



Plans to build a engineering test facility which would follow the CIT project are already underway in several countries.<sup>(7)</sup> Using the generic name of an Engineering Test Reactor (ETR) for this device, we see that current plans call for construction in 1992 and operation in the late 1990's. This test facility would expand upon the DT ignition physics learned from CIT and do a limited amount of materials and blanket component testing. Presently, it is anticipated that the testing phase would last about 12 years. No electricity would be produced by this device (except possibly from small test blankets that could be inserted into the side of the reactor).

The ETR would be followed by a Demonstration plant which would integrate the plasma, materials, and full tritium breeding blankets into one power producing facility. This Demo is expected to produce electricity, but not on a regular and certainly not on an economical, basis.

Finally, if all went well, another commercial facility would be built sequentially to the Demo, hopefully to be ordered by an electric utility. The total time from now to the first operation of this DT commercial unit could be 30 years or more.

On the other hand, if the experiments with the D-He<sup>3</sup> cycle in the ETR facility were to be successful, then an alternate schedule could be pursued. Since the D-He<sup>3</sup> fuel cycle causes much less induced radioactivity it should be possible to convert the ETR

unit directly into a power producing Demo. This is possible because, with the low neutron damage level associated with the D-He<sup>3</sup> cycle, we do not need a long testing program for materials and because we do not need to breed tritium, we do not need to test blanket concepts. Moving directly to a Demo on the same site by adding direct conversion equipment saves both time and capital investment. If the Demo can be successfully operated in an electrical producing mode for 4-5 years, we would then be ready to move to a commercial unit. The overall time savings should be between 10 and 20 years compared to the DT case and it is possibly the only way to have commercial fusion power reactors by the year 2020. This time period is important as we shall see later because it determines when we would begin to require helium-3 from nonterrestrial sources.

#### IV) WHAT ABOUT HELIUM-3 RESOURCES FOR NEAR TERM RESEARCH?

Thus far, we have not said how we would fuel the near term test reactors until we could obtain a larger external source of He<sup>3</sup> fuel. The answer lies with the terrestrial resources of He<sup>3</sup>. They lie in two categories as shown in Table IV-1.<sup>(11)</sup> The first has to do with the primordial He<sup>3</sup> present in the earth at its creation. Unfortunately, most of that He<sup>3</sup> has long since diffused from the earth and been lost through the atmosphere to outer space. What is left in any retrievable form is contained in the underground natural gas reserves. Table IV-1 shows that in the underground strategic helium storage caverns, there is some 30 kg. If we were to process the entire U.S. resource of natural gas, we might obtain another 200 kg but the cost and side effects of such a project make it very unlikely that we could do such a thing.

Table IV-1

#### Reasonably Assured Reserves of <sup>3</sup>He That Could Be Available in the Year 2000

Source	Cumulative Amount (kg)	Production Rate Post 2000 (kg/y)
TRITIUM DECAY		
● U.S. Weapons	300	15
● CANDU Reactors	10	2
PRIMORDIAL		
● He Storage	29	—
● Natural Gas	187	—
	> 550	~ 17

Another source of  $\text{He}^3$  on earth is from the decay of tritium ( $t_{1/2} = 12.3$  years). When  $\text{T}_2$  decays, it produces a  $\text{He}^3$  atom and a beta particle. Simple calculations of the inventory of  $\text{T}_2$  in U.S. thermonuclear weapons shows that if the  $\text{He}^3$  were collected, some 300 kg would be available by the year 2000. Presumably about the same amount of  $\text{He}^3$  would be available from the weapons stockpile of the USSR. The equilibrium production of  $\text{He}^3$  (assuming no future change in weapons stockpiles) is around 15 kg per

One could also get much smaller amounts of  $\text{He}^3$  from the  $\text{T}_2$  produced in the heavy water coolants of Canadian CANDU reactors. This could amount to 10 kg of  $\text{He}^3$  by the year 2000 and  $\text{He}^3$  will continue to be generated at a rate of 2 kg per year thereafter.

We note again that 1 kg of  $\text{He}^3$ , when burned with 0.67 kg of D, produces approximately 19 MW-y of energy. This means that by the turn of the century, we could have several hundred kg's of  $\text{He}^3$  at our disposal which could provide for several thousand MW-y of power production. The equilibrium generation rate from  $\text{T}_2$  resources could fuel a 500 MWe plant continuously if it were run 50% of the time.

Clearly, there is enough  $\text{He}^3$  to build an ETR (few hundred MW running 10-20% of a year) and a Demonstration power plant of hundreds of MWe run for several years. This could be done without ever having to leave the earth for fuel. The real problem would come when the first large (GWe) commercial plants could be built, around 2020. The next major question is can we get the  $\text{He}^3$  fuel from the moon on a time scale consistent with our development path?

#### V) WHAT AND WHERE ARE THE $\text{He}^3$ RESOURCES ON THE MOON?

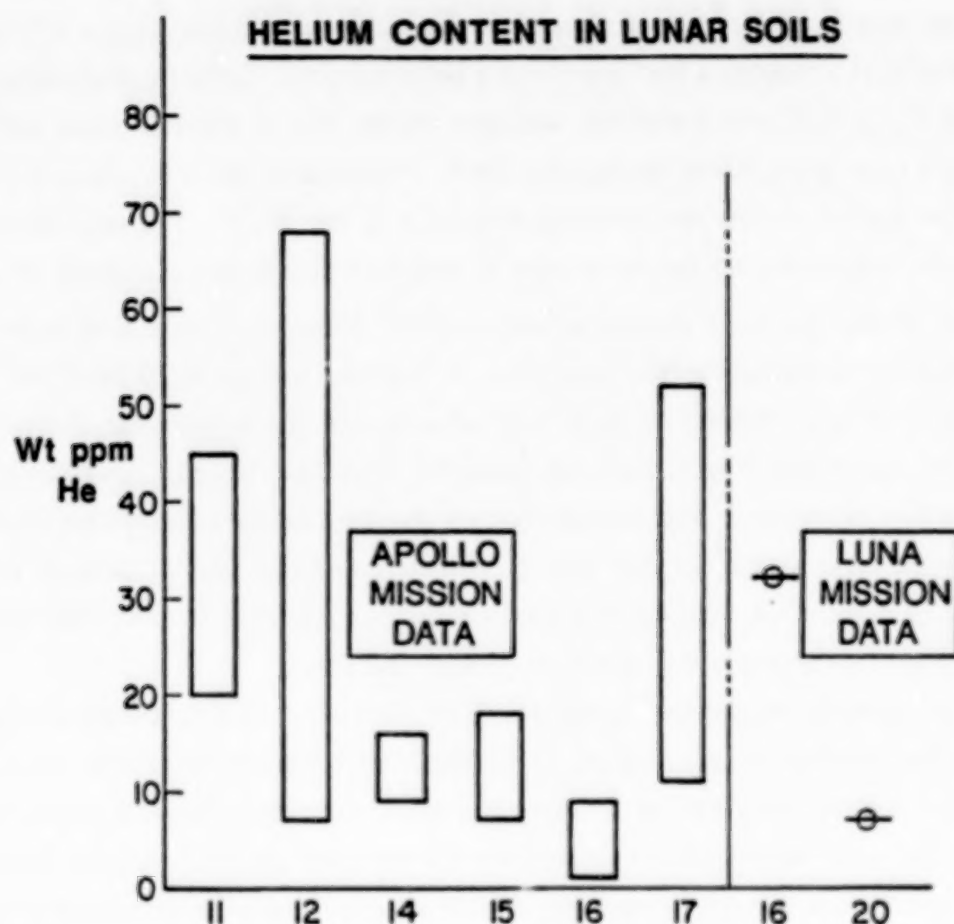
Wittenberg et al. first published their discovery of  $\text{He}^3$  in the regoliths on the moon in September 1986.<sup>(11)</sup> Since that time, work by the Wisconsin group has elaborated on the original idea. A few highlights will be summarized here.

The origin of the main source of lunar  $\text{He}^3$  is from the solar wind. Using data which showed that the solar wind contains ~4% helium atoms and that the  $\text{He}^3/\text{He}^4$  ratio is ~ 480 appm, it was calculated that the surface of the moon was bombarded with over 250 million metric tonnes in 4 billion years. Furthermore, because the energy of the solar wind is low (~3 keV for the  $\text{He}^3$  ions) the ions did not penetrate very far into the surfaces of the regolith particles (< 0.1 micron). The fact that the surface of the moon is periodically stirred as the result of frequent meteorite impacts results in the helium being trapped in soil particles to depths of several meters.

Analysis of Apollo and Luna regolith samples revealed that the total helium content in the moon minerals ranges from a few to 70 wtpm (see Figure V-1<sup>(25)</sup>). The higher concentrations are associated with the regolith on basaltic Maria of the moon and the lower contents associated with the Highland rocks and Basin Ejecta. Clearly the higher



Figure V-1

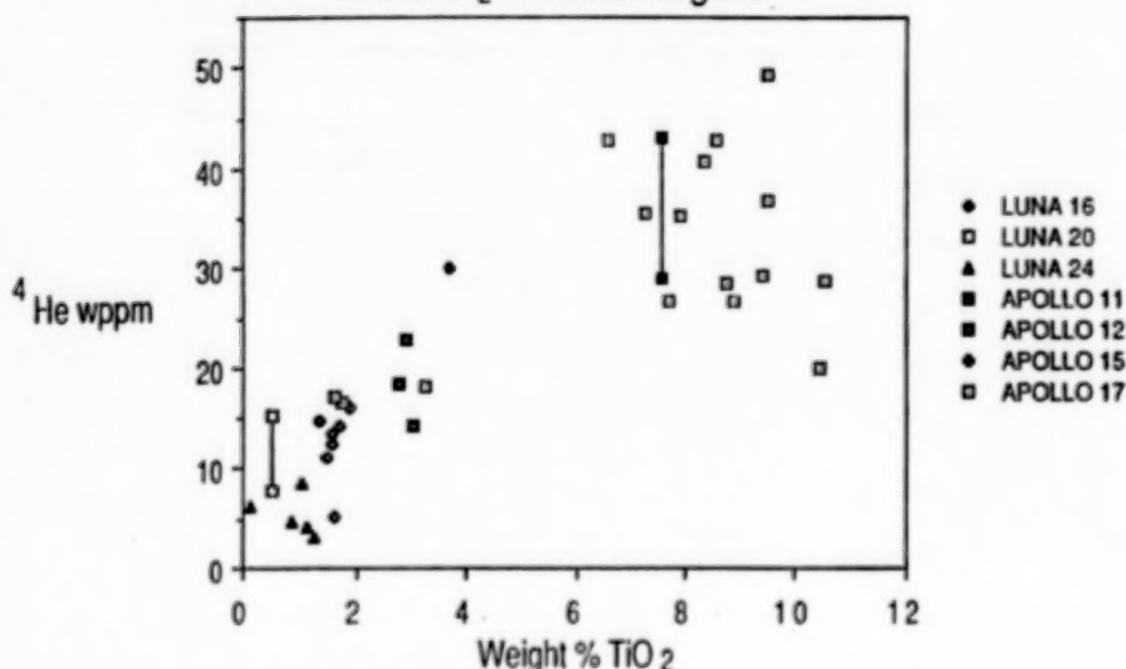


concentrations are in the most accessible and minable material. Using the data available, it is calculated that roughly a million metric tonnes of  $\text{He}^3$  are still trapped in the surface of the moon.<sup>(11)</sup>

The next step is to determine the most favorable location for extracting this fuel. Cameron<sup>(25)</sup> has shown (Figure V-2) that there is an apparent association between the He and  $\text{TiO}_2$  content in the samples. Assuming that this is generally true, he then examined the data on spectral reflectance and spectroscopy of the moon which showed that the Sea of Tranquility (confirmed by Apollo 11 samples) and certain parts of the Oceanus Procellarum were particularly rich in  $\text{TiO}_2$ . It was then determined, on the basis of the large area ( $190,000 \text{ km}^2$ ) and past U.S. experience, that the Sea of Tranquility would be the prime target for initial investigations of lunar mining sites. This one area alone appears to contain more than 8,000 tonnes of  $\text{He}^3$  to a depth of 2 meters. A backup target is the  $\text{TiO}_2$  rich basalt regolith in the vicinity of Mare Serenitatis sampled during Apollo 17<sup>(26)</sup>.

Figure V-2

### Relationship Between Helium Content and $\text{TiO}_2$ in Lunar Regolith



#### VI) HOW WOULD THE $\text{He}^3$ BE EXTRACTED?

Since the solar wind gases are weakly bound in the lunar regolith it should be relatively easy to extract them. Pepin<sup>(27)</sup> found (Figure VI-1) that heating lunar regolith caused the  $\text{He}^3$  to be evolved above 200° C and by 600° C, 75% of the fuel could be removed.

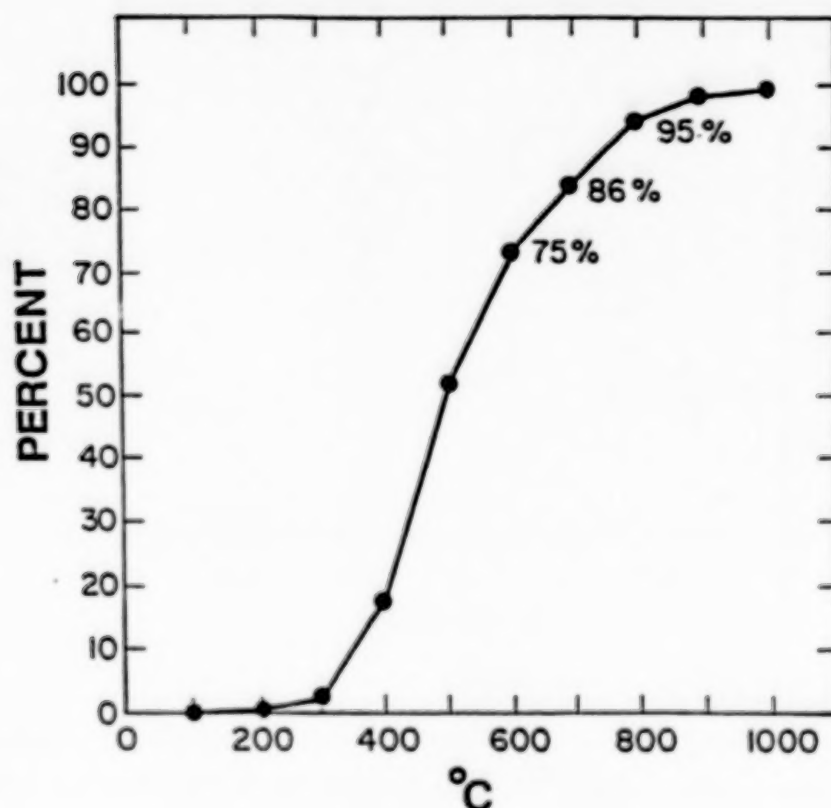
There are several methods by which the  $\text{He}^3$  could be extracted and a schematic of one approach is shown in Figure VI-2. In this unit, the loose regolith, to a depth of 60 cm, is scooped into the front of the robotic unit. It is then sized to particles less than 100 microns in diameter because there seems to be a higher concentration of solar gases in the smaller particles (presumably because of the high surface to volume ratio).<sup>(28)</sup> After beneficiation, the concentrate is preheated (Figure VI-3) by heat pipes<sup>(29)</sup> and then fed into a solar heated retort. At this point we anticipate only heating to 600 or 700° C and collecting the volatiles emitted at that temperature ( $\text{H}_2$ ,  $\text{He}^4$ ,  $\text{He}^3$ , C compounds,  $\text{N}_2$ ). The gases are collected and the spent concentrate is discharged through heat pipes to recover 90% of its heat. The concentrate is finally dropped off the back of the moving miner. Note that in the 1/6 gravity environment relatively little energy is expended lifting material!

Of course, this scheme would only work during the lunar day but orbiting mirrors, nuclear reactor heat from a mobile power plant, or indirect heating from microwaves generated at a central power plant on the moon could extend the operating time.

Figure VI-1

# HELIUM-3 EVOLUTION FROM LUNAR SOIL

Data from Pepin et al., 1970



Alternative schemes are being examined through parametric analyses of such variables as particle size vs. temperature vs. yield, mining depth vs.  $\text{He}^3$  concentration vs. particle size distribution, manned operation vs. robotic operations vs. maintenance costs, mechanical particle separation vs. gaseous particle separation vs. yield, solar vs. nuclear power, etc.

Once the volatiles are extracted, they can be separated from the helium by isolation from the lunar surface and exposure to outer space ( $< 5^\circ \text{K}$ ) during the lunar night. Everything except the He will condense and the  $\text{He}^3$  can be later separated from the  $\text{He}^4$  by superleak techniques well established in industry.<sup>(30)</sup>

For every tonne of  $\text{He}^3$  produced, some 3300 tonnes of  $\text{He}^4$ , 500 tonnes of nitrogen, over 3000 tonnes of CO and  $\text{CO}_2$  and 6100 tonnes of  $\text{H}_2$  gas are produced. The  $\text{H}_2$  will be extremely beneficial on the moon for lunar inhabitants to make water and for propellants. Transportation of that much  $\text{H}_2$  to the moon, even at 200 \$/per kg, would cost -1 billion dollars (for every tonne of  $\text{He}^3$  produced). As previously noted, the  $\text{He}^3$  itself could be worth as much as -1 billion dollars per tonne. Of the other volatiles, the  $\text{N}_2$

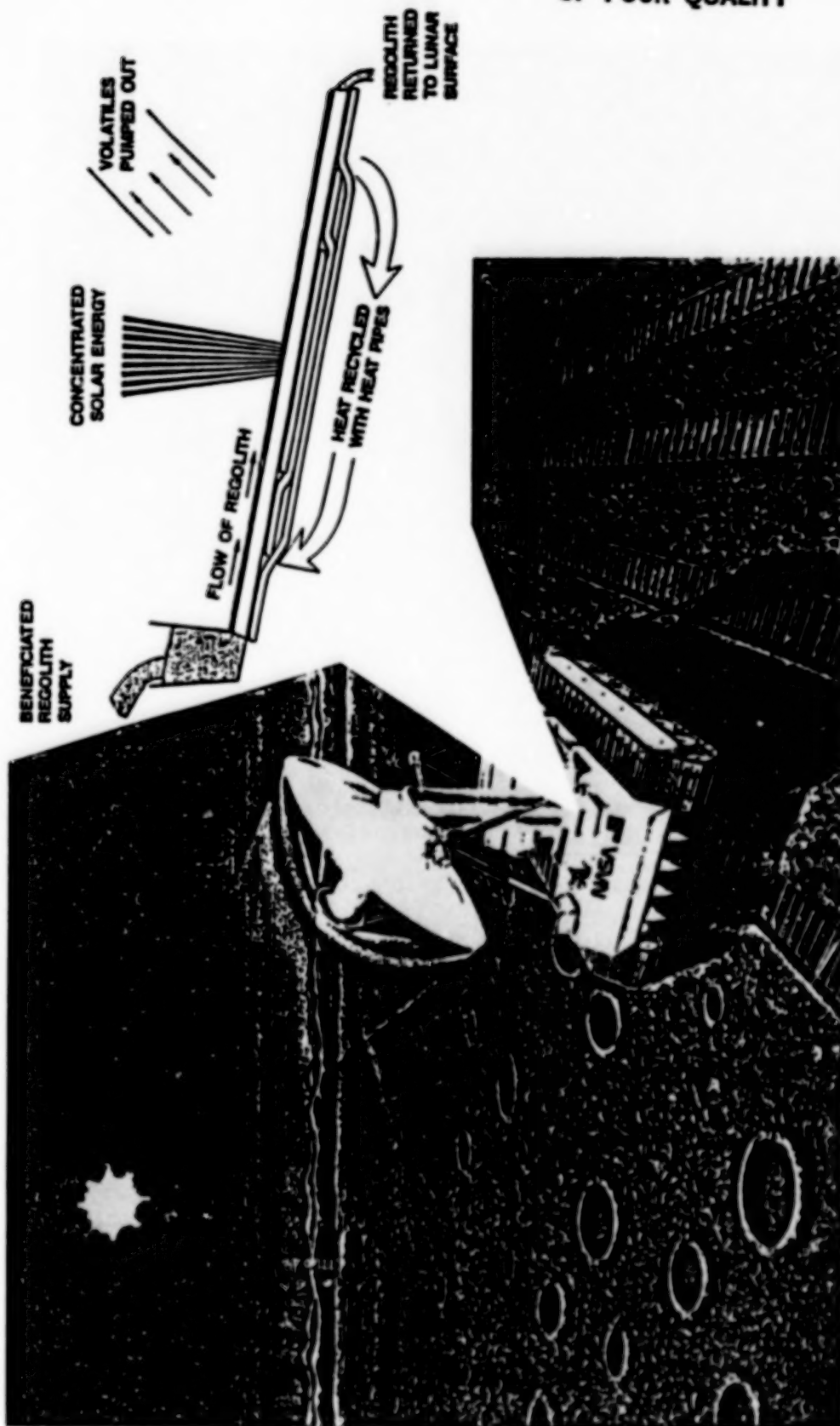
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Figure VI-2. Design of lunar vehicle to extract He-3 from regolith using direct solar radiation.





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SCHEMATIC OF ONE POSSIBLE TECHNIQUE FOR THE  
EXTRACTION OF VOLATILES FROM LUNAR REGOLITH

could also be used for plant growing, the carbon for manufacturing or atmosphere control, and the  $\text{He}^4$  for pressurization and as a power plant working fluid.

## VII) HOW MUCH IS THE $\text{He}^3$ WORTH?

While it is hard to anticipate the cost of energy in the future, we can base our calculations on today's experience. First of all, it is worthwhile to get a feeling for how much energy is contained in the  $\text{He}^3$  on the moon. If the resource is 1 million metric tonnes, then there is some 20,000 TW-y of potential thermal energy on the moon. This is over 10 times more energy than that contained in economically recoverable fossil fuels on earth.

The second point to note is that only 20 tonnes of  $\text{He}^3$ , burned with  $\text{D}_2$ , would have provided the entire U.S. electrical consumption in 1986 (some 285 GWe-y). The 20 tonnes of condensed  $\text{He}^3$  could fit in the cargo bay of just one US shuttle craft.

In 1986, the U.S. spent 40 billion dollars for fuel (coal, oil, gas, uranium) to generate electricity. This does not include plant or distribution costs, just the expenditure for fuel. If the 20 tonnes of  $\text{He}^3$  just replaced that fuel cost (and the plant costs and distribution costs stayed the same) then the  $\text{He}^3$  would be worth approximately 2 billion dollars per tonne. At that rate it is the only thing we know of on the moon which is economically worth bringing back to earth assuming that, early in the 21st century, the incremental cost for a  $\text{He}^3$  mining operation could be less than -50 billion dollars. (In fact, it is the only element that the moon has in relatively large quantity that we do not have on earth.)

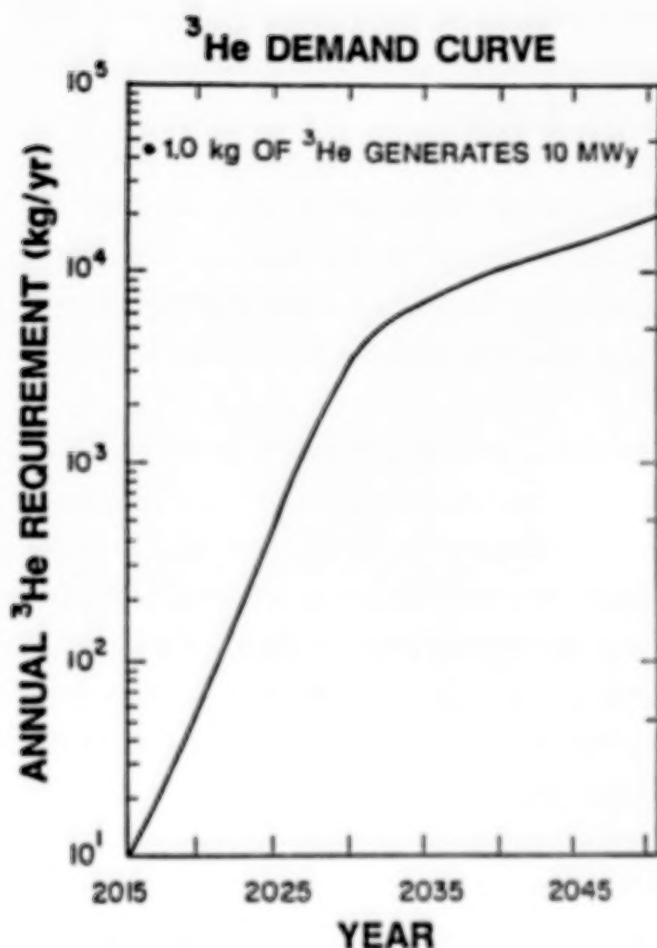
It is our opinion at this time, that a realistic figure for the worth of  $\text{He}^3$  on the earth is -1 billion dollars per tonne. This is because the cost of the fusion power plants themselves are probably as expensive as fission plants which in turn, are more expensive than coal plants.

We have not factored in the credit for the other solar wind gases that would be extracted but it is possible that the cost of operating the mining base might be offset by the auxiliary products produced leaving the value of  $\text{He}^3$  to be applied against capital costs and profit. Further economic studies are underway as are other options for the mining, beneficiation and extraction of this fusion fuel.

## VIII) IS THE TIME TABLE REALISTIC?

It was shown in section III that no  $\text{He}^3$  would probably be required from the moon before 2015. A recent study by Sviatoslavsky,<sup>(31)</sup> using conservative U.S. energy growth rates (2%) and conservative penetration rates of fusion beginning with the first plant in 2015, produced the  $\text{He}^3$  demand curve shown in Figure VIII-1. This demand results in the

Figure VIII-1



cumulative  $\text{He}^3$  requirements shown in Figure VII-2. It can be seen that the demand reaches the -1 tonne per year level in 2030, 10 tonnes per year in 2035 and by 2050, nearly 200 tonnes of  $\text{He}^3$  could be required.

This schedule should be compared to future activities in space proposed by the recent National Commission on Space (NCOS) report<sup>(32)</sup> shown in Figure VIII-3. This plan envisions the first lunar base to be established by 2005 with the first pilot plant production of oxygen by 2010. By 2015 it is anticipated that some 500 tonnes of oxygen per year could be exported from the moon to the space station (compare this to 1 tonne of  $\text{He}^3$  per year required a decade later). Furthermore the extraction of oxygen has to be done at 1300° C, a much more difficult job than working at 700° C for  $\text{He}^3$ .

Therefore, it seems that the schedule and technology requirements required to extract  $\text{He}^3$  from the moon are consistent with current proposals to procure oxygen for the space station or to place a colony on Mars.

Figure VIII-2

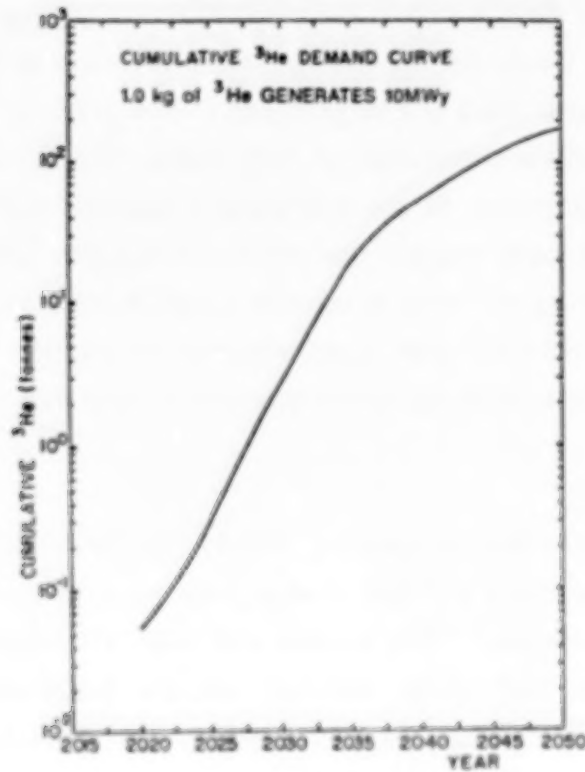
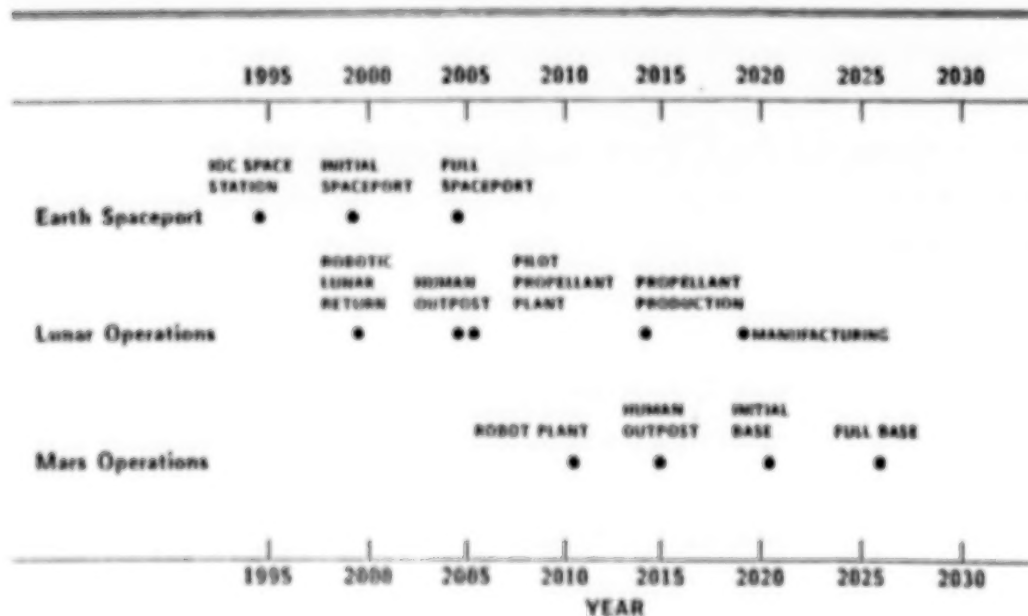


Figure VIII-3

### *Present Plans for Access to the Inner Solar System*





## IX) CONCLUSIONS

Two major consequences can evolve from this work. First, there is a reasonable possibility that we could have a clean and inherently safe nuclear power source in the 21st century which will insure the survival of life and society as we know it on earth. Secondly, the discovery that there is a large source of energy on our nearest neighbor in the solar system opens up the exploration of outer space. This not only provides us with an economic incentive to return to the moon, but it can also make the settlement of space much more economically feasible than previously thought. Therefore, the successful demonstration of burning  $\text{He}^3$  with D takes on added importance in the near term and the successful establishment of lunar bases becomes critical for the long term. Our grandchildren will be greatly affected by the outcome of these two noble endeavors.

## X) ACKNOWLEDGEMENT

This work was supported in part by NASA, the University of Wisconsin, the Grainger Foundation, the Electric Power Research Institute, and the Wisconsin Electric Utilities Research Foundation. The authors also wish to acknowledge the help of scientists in the Fusion Technology Institute and the Wisconsin Center for Space Automation and Robotics. Special thanks is given to Drs. Attaya, Cameron, Emmert, Santarius, Sawan, Sviatoslavsky, and Wittenberg for permission to quote unpublished results.

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- 31) I.N. Sviatoslavsky, "Preliminary He<sup>3</sup> Demand Requirements for Commercial Fusion", Univ. of Wisconsin Report, WCSAR-TR-AR3-8709 (1987).
- 32) "Pioneering the Space Frontier"; Report of the National Commission on Space, Bantam Books, 1986.

### Recent DHe-3 Results in JET-March 1988

DHe-3 Thermonuclear Power	50 kW
Electron Temperature	9-10 keV
Ion Temperature	10 keV
Q ( $P_{out}/P_{in}$ )	~0.005
Energy Confinement Time	0.4 s

### Expected Results - May/June 1988

- 100's of kW's of thermonuclear power DHe-3
- Significantly improved Q's
- $T_e = 15$  to 20 keV

### Recommended Action Items Related to Terrestrial Use of He-3 Fuel

#### NASA-SPECIFIC ACTION

- Perform experiments to demonstrate the methodologies for mining, beneficiation and processing of lunar material for He-3
- Evaluate candidate He-3 mining sites
- Examine benefits of byproducts of DHe-3 mining to lunar base development and solar system exploration

*Recommended Action Items Related  
to Terrestrial Use of He-3 Fuel*

---

NASA-SPECIFIC ACTION

- Examine legal implications of lunar He-3 recovery
- Perform an economic analysis of total costs and benefits of recovering He-3 and byproducts from the moon
- Establish one or more Centers of Excellence for terrestrial and space fusion power applications of lunar He-3

*Recommended Action Items Related  
to Terrestrial Use of He-3 Fuel*

---

DOE-SPECIFIC ACTION

- Plan early DHe-3 tests in next generation (CIT and ITER) D-T fusion experiments
- Conduct an intense, short-term study of the physics and technology requirements for DHe-3 as compared with DT
- Initiate design and experimental studies of direct electrostatic and electromagnetic conversion of DHe-3 fusion energy to electricity in toroidal concepts
- Perform detailed analyses of safety, environmental, and economic features of commercial DHe-3 reactors



*Recommended Action Items Related  
to Terrestrial Use of He-3 Fuel*

---

COORDINATED ACTION

- Establish a joint NASA/DOE plan for lunar He-3 recovery and commercialization
  
- Promote private sector participation in lunar He-3 recovery and utilization
  
- Explore the possibility of an international He-3 fusion development effort (e.g. INTERLUNE)

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HELIUM-3 BLANKETS FOR TRITIUM BREEDING IN FUSION REACTORS

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# OBSERVATIONS

- RESOURCE CONSIDERATIONS HAVE LIMITED D-T FUSION REACTOR BLANKET STUDIES TO LITHIUM-BASED SYSTEMS
- WHILE ACCEPTABLE LITHIUM-BASED BLANKET DESIGNS HAVE BEEN DEVELOPED SAFETY & ENGINEERING CONCERNS ARE ASSOCIATED WITH THE USE OF LITHIUM
- THE BEST SAFETY FEATURES ARE GENERALLY ATTRIBUTED TO BLANKETS EMPLOYING HELIUM AS COOLANT
- IT WOULD BE DESIRABLE TO DEVELOP A TRITIUM BREEDING OPTION WHICH RETAINS HELIUM AS COOLANT AND ELIMINATES LITHIUM CONCERNS
- A HELIUM-3 (BREEDER)/HELIUM-4 (COOLANT) BLANKET OFFERS PROMISE FOR ENHANCED SAFETY & ENGINEERING CHARACTERISTICS

## ESECOM RESULTS

FUSION TECHNOLOGY/JAN., 1988

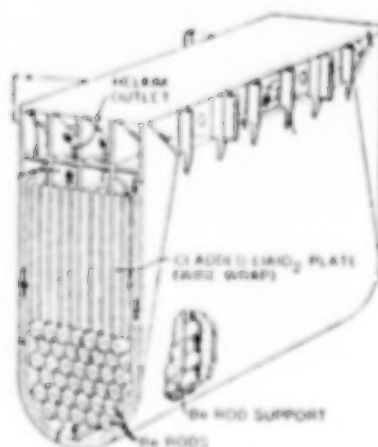
Case	Nominal LSA	COE (mill/kW·h)
1. V-Li/TOK	3	49.7
2. RAF-He/TOK	2	42.6
3. RAF-PbLi/RFP	4	37.7
4. V-Li/RFP	4	37.3
5. SiC-He/TOK	1	40.3
6. V-Flibe/TOK	2	42.9
7. V-MHD/TOK	4	35.4
8. V-D <sup>3</sup> He/TOK	2	41.3
9. RAF-Li/HYB	4	
Stand alone		63.7
With MHTGR clients		40.3
10. SS-He/HYB	4	
Stand alone		55.8
With MHTGR clients		39.8



## GENERAL FEATURES OF CONCEPT

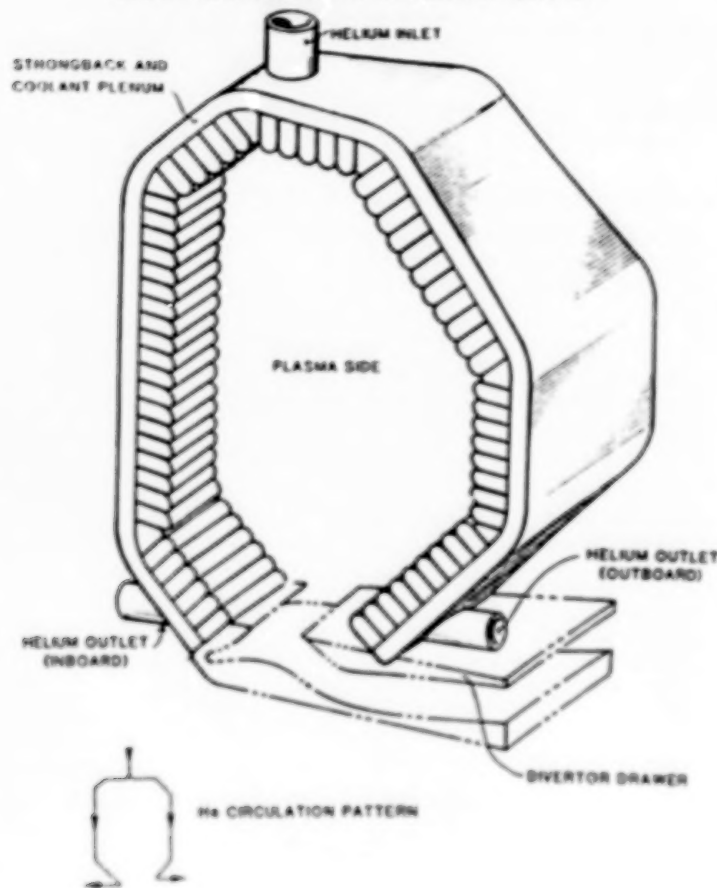
- USE HELIUM-3 TO BREED TRITIUM  
[large  $\sigma(n,T)$  of  $^3\text{He}$ ]
- BLANKET COOLANT WOULD BE HELIUM-4
  - OPERATING AT ABOUT 5 MPa
  - 100 - 300 C (NEAR TERM)
  - 250 - 500 C (COMMERCIAL)
- BLANKET STRUCTURE WOULD BE CONVENTIONAL (e.g. STAINLESS STEEL) OR ADVANCED (e.g. SiC)
- BERYLLIUM WOULD BE USED FOR NEUTRON MULTIPLICATION [large  $\sigma(n,2n)$ ]
- HELIUM-3 CONTAINED IN A LOOP SEPARATE FROM HELIUM-4 LOOP AND FLOWS WITHIN THE BERYLLIUM, ALSO ACTING AS A PURGE FOR BERYLLIUM-BRED TRITIUM
- CONCEPT FEATURES SIMILAR TO THOSE OF A He/SB BLANKET WITH EXCEPTION THAT ISSUES ASSOCIATED WITH THE SB ARE ELIMINATED

A REFERENCE CONFIGURATION WAS ADOPTED BASED ON MINOR MODIFICATIONS TO THE BCSS He/LiAlO<sub>2</sub>/Be BLANKET

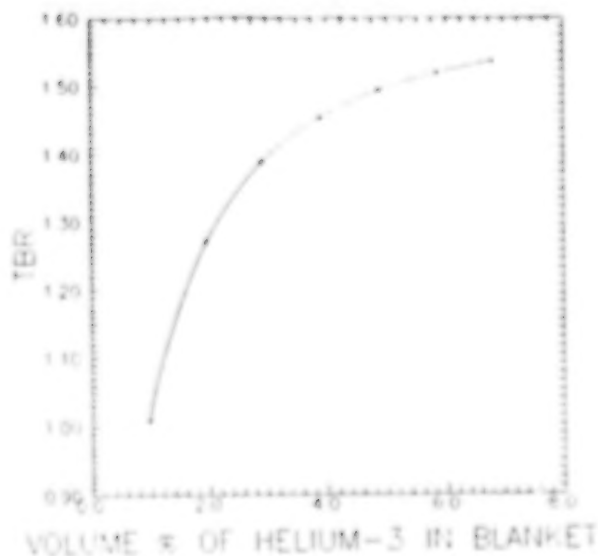


LiAlO<sub>2</sub> IS REPLACED WITH BERYLLIUM CONTAINING A HELIUM-3 PURGE STREAM

# HELIUM COOLED BLANKET MODULE SECTOR



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- THE HELIUM-3 BLANKET EXHIBITS GOOD TRITIUM BREEDING POTENTIAL
- THE REFERENCE CONFIGURATION WAS NOT OPTIMIZED FOR TBR & SOME BREEDING ENHANCEMENT IS EXPECTED

**THE HELIUM-3 BLANKET CONCEPT SHARES  
MANY ATTRACTIVE ASPECTS OF He/SB BLANKETS  
AND BRINGS SEVERAL ADVANTAGES**

• **COMMON ATTRACTIVE FEATURES**

- GOOD SAFETY CHARACTERISTICS
- NO CORROSION CONCERNS
- GOOD TRITIUM BREEDING POTENTIAL

• **ADVANTAGES OF HELIUM-3 BLANKETS**

- ONLINE BREEDING CONTROL
- NOT SENSITIVE TO POWER VARIATIONS &  
HEAT CONDUCTANCE CONSTRAINTS
- REDUCED TRITIUM INVENTORY IN BREEDER
- NO C-14 PRODUCTION IN BREEDER

- The R & D REQUIRED FOR THE HELIUM-3 BLANKET  
WOULD BE SIMILAR TO THAT OF He/SB BLANKETS  
WITH EXCEPTION OF SB DEVELOPMENT

**TRITIUM CONTROL ISSUES IN ESECOM REFERENCE CASES**

Case	Active Tritium Inventory (g)	Dominant Location of Tritium	Difficulty of Control
V-Li/TOK	500	Coolant/breeder	Low
RAF-He/TOK	160	Breeder	Low to medium
RAF-PbLi/RFP	60	Coolant	Medium to high
V-Li/RFP	500	Coolant/breeder	Low
SC-He/TOK	160	Breeder	Low to medium
V-PbLi/TOK	15	Structure	Medium
V-MHD/TOK	Not estimated	Structure?	Medium?
V-D <sup>3</sup> He/TOK	60	Coolant	Low to medium
RAF-Li/HYB	1000	Coolant/breeder	Low
SS-He/HYB	200	Structure	Low to medium

## T/He3 Inventory and Leakage

- Purge circuit He3 volume:
  - Blanket/plenum - 10 m3
  - Piping/T system/misc - 5 m3
- Inventories:
  - He4 coolant - 2000 kg
  - He3 purge - 50 kg
  - T in purge - 0.06 g
  - T in coolant - 0.8 g
  - T in Be - 0.5-1000 g (?)
- Assume 1% circuit leakage/yr (BCSS):
  - He4 - 2 kg/yr
  - He3 - 0.5 kg/yr
  - T - 100 Ci/yr (+ 10 Ci/d across HX)
- Options for He3 inventory reduction:
  - Breeding in outboard only - 25% less
  - Purge flow rate to 30 m/s - 10% less

## HELIUM-3 REQUIREMENTS FOR FUSION

---

	ITER <sup>a</sup>	COMM <sup>a</sup>	100 x COMM
INVENTORY, kg	50	50	5000
LEAKAGE, kg/yr	0.5	0.5	50
BURNUP, kg/yr	8	96	9600
LIFETIME, kg	85 (10 yrs)	3800 (40 yrs)	10 <sup>b</sup> (120 yrs)
COST, \$/g	700 (MOUND)	100-500 (TARGET)	100-500 (TARGET)

---

<sup>a</sup> 600 MW, / 25 % AVAILABILITY

<sup>b</sup> 2400 MW, / 75 % AVAILABILITY



**RESERVES OF HELIUM-3 THAT COULD BE  
AVAILABLE IN THE YEAR 2000**

SOURCE	CUMULATIVE AMOUNT TO YEAR 2000 (kg)	PRODUCTION RATE POST YEAR 2000 (kg/yr)
Decay of T, DOE		
MRC annual sales	—	1.3
MRC inventory	> 13.4	—
CANDU reactors	10	2
US weapons (approximate)	~ 300	~ 15
Natural gas wells underground storage	29	—
Known reserves	187	—
Total	500 to 600	~ 18

Note: Data from the University of Wisconsin (Fusion Technology)

- THE DECAY OF TRITIUM IN MILITARY STOCKPILES COULD SATISFY THE HELIUM-3 REQUIREMENTS OF ITER
- COMMERCIAL FUSION POWER WOULD REQUIRE EXTRATERRESTRIAL SUPPLIES OF HELIUM-3

**CONCLUDING REMARKS**

- HELIUM-3 BLANKETS OFFERS CONSIDERABLE PROMISE FOR TRITIUM BREEDING IN FUSION REACTORS
  - GOOD BREEDING POTENTIAL
  - LOW OPERATIONAL RISK
  - ATTRACTIVE SAFETY FEATURES
- AVAILABILITY OF HELIUM-3 RESOURCES IS THE KEY ISSUE FOR THIS CONCEPT
  - THERE IS SUFFICIENT HELIUM-3 FROM DECAY OF MILITARY STOCKPILES TO MEET ITER NEEDS
  - EXTRATERRESTRIAL SOURCES OF HELIUM-3 WOULD BE REQUIRED FOR A FUSION POWER ECONOMY
    - ~ 100 - 500 g/g
    - ~ 10<sup>6</sup> kg/yr & ~ 10<sup>8</sup> kg

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STATUS OF FUSION RESEARCH AND IMPLICATIONS FOR D-<sup>3</sup>He SYSTEMS

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World-wide programs in both magnetic confinement and inertial confinement fusion research have made steady progress towards the experimental demonstration of energy breakeven.<sup>(1-4)</sup> Both approaches are now in reach of this goal within the next few years using a D-T equivalent plasma. For magnetic confinement, this step is expected in one of the large tokamak experimental devices such as TFTR (USA), JET (EC), JT-60 (Japan), or T-15 (USSR). Upgraded versions of the Nova glass laser (USA) and GEKKO (Japan) also appear to have a good chance at this goal. The light-ion beam facility "PBFA-II" is viewed as a "dark horse" candidate. Recent physics parameters obtained in these various experiments will be briefly reviewed in this presentation.

However, after breakeven is achieved, considerable time and effort must still be expended to develop a usable power plant. The time schedules envisioned by workers in the various countries involved are fairly similar.<sup>(1-3)</sup> For example, the European Community (EC) proposes to go from the physics studies in JET to an engineering test reactor (NET) which has a construction decision in 1991. This is projected to result in a demonstration reactor after 2015. Plans for inertial confinement are currently centered on the development of a "next-step" target facility based on an advanced 5-megajoule laser on roughly the same time scale as NET.<sup>(5)</sup> The facilities required for both magnetic and inertial confinement will be large and expensive. Consequently, international cooperation is receiving strong consideration for the next magnetic facility, namely ITER (International Thermonuclear Experimental Reactor). This project would be shared by the USA, EC, USSR, and JAPAN.

The main program described above is focused on D-T devices. For burning advanced fuels such as D-<sup>3</sup>He however, alternate confinement concepts with high (> 30%) plasma beta (magnetic confinement)<sup>(6)</sup> or a D-T seed ignited burn<sup>(7)</sup> (inertial confinement) appear necessary. These alternatives have less of a physics data base than the tokamak and conventional inertial targets. Thus, the possibility of success is less certain and the best approach not so clear.

In magnetic confinement, three of the most promising high beta approaches with a reasonable experimental data base are the Field Reversed Configuration (FRC), the high field tokamak, and the dense Z-pinch. The best experimental data from an FRC is roughly an order of magnitude lower in temperature and 2 orders of magnitude less in Lawson n<sub>t</sub> than the best tokamak results.<sup>(8)</sup> However, these results were achieved with a much smaller, less costly experimental device. Also a number of key issues such as control of certain instabilities and the establishment of methods for adiabatic compression and translation have been resolved.<sup>(9)</sup> A high-field tokamak has just become operational in the USSR while the Ignitor Apparatus is being designed in Italy. A related device, CIT, is proposed as a "next-step" ignition experiment in the U. S. Z-pinch studies in both the U. S. and Europe have made rapid strides with the discovery that a relatively stable pinch can be formed by passing a high current discharge through a thin deuterium fiber. Consequently, there appears to be a solid physics data base to build on in these areas if a development plan to burn D-<sup>3</sup>He is desired.



The situation is less clear in inertial confinement where the first step requires an experimental demonstration of D-T spark ignition. It appears that this must wait for the next generation of high-powered laser drivers combined with advanced target designs.

In conclusion, it appears that fusion research has reached a point in time where an R&D plan to develop a D-<sup>3</sup>He fusion reactor can be laid out with some confidence of success. Such a plan could build on the continuing progress in D-T studies, but the development of an alternate confinement concept(s) would be essential. Because engineering problems (e.g., tritium breeding and neutron damage to materials) are reduced and an approach such as the FRC involves relatively small experimental devices, the D-<sup>3</sup>He development program appears to be much less expensive than the D-T tokamak program. Also, as shown by several reactor studies (e.g., see Ref. 10), the resulting reactor is thought to boast important benefits with improved environmental compatibility, small size, higher efficiency, and favorable economics.

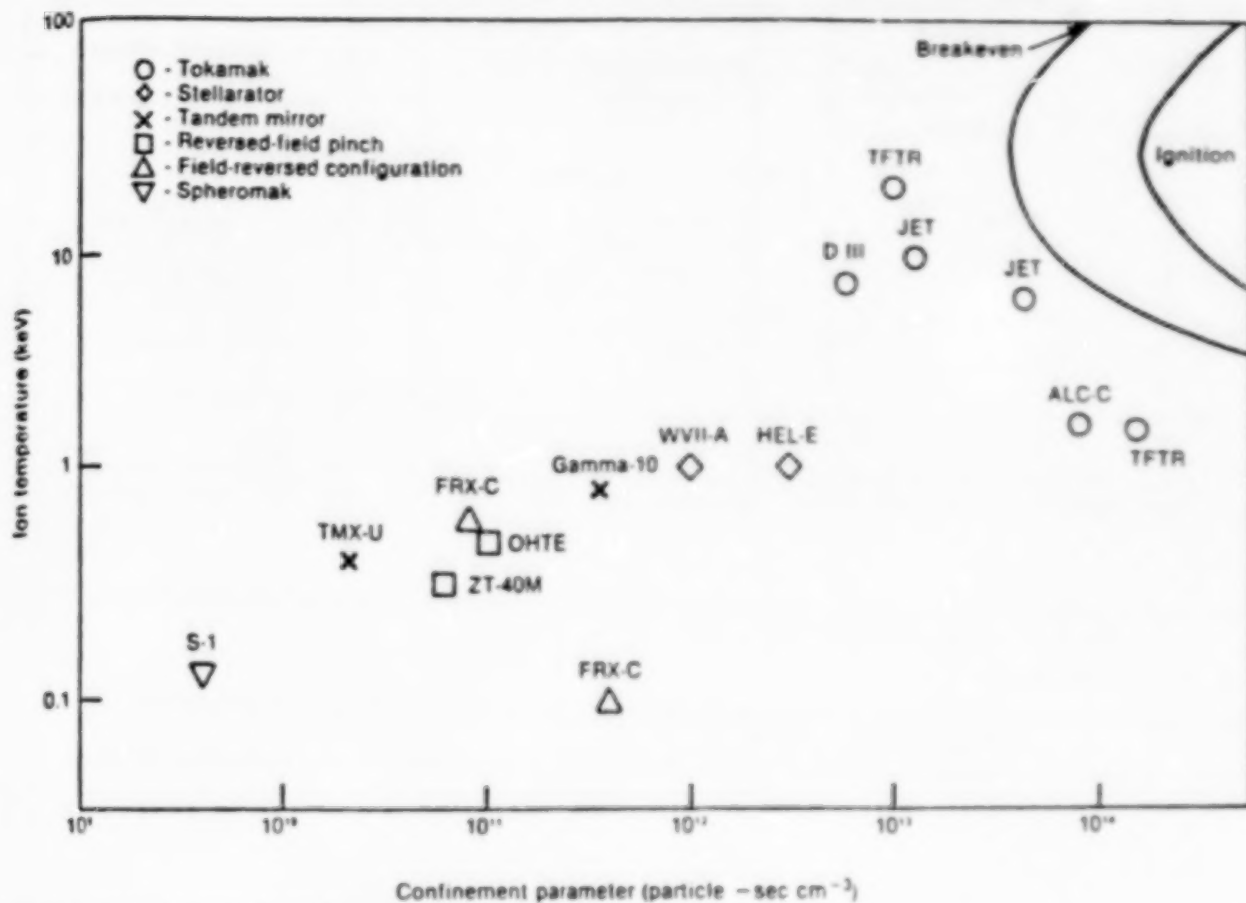
1. TPA Plasma Science Final Report, U. of Wisconsin, December 1986.
2. Technical Planning Activity Final Report, ANL/FPP-87-1, Argonne National Laboratory, January 1987.
3. Starpower: The U. S. and the International Quest for Fusion Energy, OTA-E-338, U. S. Government Printing Office, Oct. 1987.
4. Review of the Department of Energy's Inertial Confinement Fusion Program, National Academy of Sciences, March 1986.
5. D. Bixler, "On Achieving a Laboratory Microfusion Capability," Proceedings, Workshop on Laser Interaction and Related Plasma Phenomena (H. Hora and G. Miley, eds.) Monterey, CA (1988).
6. G. H. Miley, "Potential and Status of Alternate-Fuel Fusion," 4th ANS Topical Mtg. on the Technology of Controlled Nucl. Fusion, Vol. 1, p. 905, King of Prussia, PA, 1980.
7. G. H. Miley, "Advanced-Fuel Targets for Beam Fusion," Proceedings of the 6th International Conference on High-Power Particle Beams (BEAMS '86), p. 309, Kobe, Japan, 1986..
8. M. G. Tuszewski, "Field-Reversed Configurations without Toroidal Field," Los Alamos National Lab. Report LA-UR-88-945 (1988).
9. B. Coppi, "Ignition Experiments and Physics: Ten Years Later," Intern. School of Plasma Phys. Workshop on Basic Phys. Processes of Toroidal Fusion Plasmas, Vol. II, 713, Varenna, Italy, 1985.
10. G. H. Miley, J. G. Gilligan and D. Driemeyer, "Preliminary Design of a Self-Sustained, Advanced-Fuel Field Reversed Mirror Reactor-SAFFIRE," *Trans. Am. Nucl. Soc.*, 30, 47 (1978).

# PROGRESS TO DATE IN FUSION RESEARCH AND DEVELOPMENT

## Large Tokamak Facilities

Characteristic	TFTR	JET	JT-60	T-15
Location	USA	EC/UK	Japan	USSR
Experimental Start	1982	1983	1985	1987
Major Radius (m)	2.5	3.0	3.0	2.4
Minor Radius (m)	0.85	1.25	0.95	0.70
Elongation	1.0	1.6	1.0	1.0
Toroidal Field (T)	5.2	3.5	4.5	3.0
Plasma Current (MA)	3.0	5.0	2.7	2.3
Auxiliary Heating (MW)	30	40	30	30
Heating Pulse (s)	2	10	5	>1
Heating Methods	Neutral Beam (NB) ICRH	ICRH NB	NB LHH ICRH	ECH NB
Working Gas	H,D,DT	H,D,DT	H,D	H
Special Features	Adiabatic compression Tangential NB	D-Shape	Outer divertor	Super-conducting coils
Program Emphasis	Confinement at high nT  DT breakeven	Confinement at high $\beta$  High-power rf  Plasma shaping Alpha physics	Confinement at high nT  High-power rf  Divertor	ECH  Plasma control

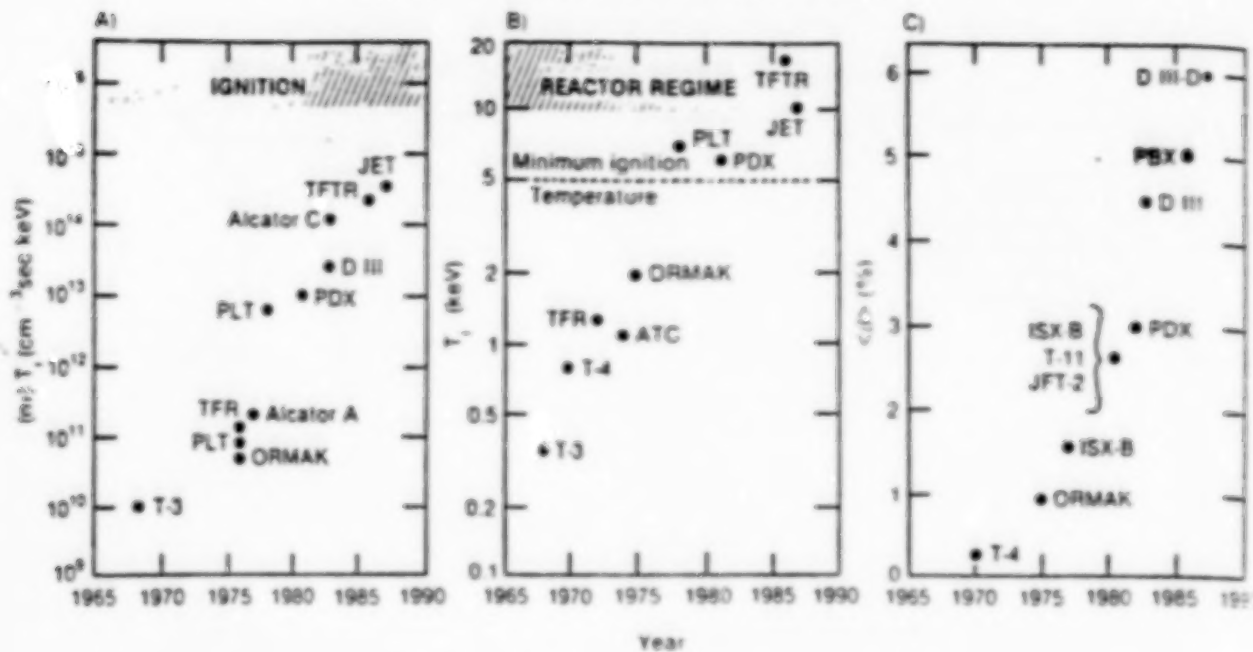
Plasma Parameters Achieved by Various Confinement Concepts



KEY: S-1 Spheromak I, Princeton Plasma Physics Laboratory, Princeton, NJ  
 TMX-U Tandem Mirror Experiment Upgrade, Lawrence Livermore National Laboratory, Livermore, CA  
 ZT-40M Toroidal Z pinch, 40, Modified, Los Alamos National Laboratory, Los Alamos, NM  
 FRX-C Field Reversed Experiment C, Los Alamos National Laboratory, Los Alamos, NM  
 OHTE Ohmically Heated Toroidal Experiment, GA Technologies, Inc., San Diego, CA  
 Gamma-10 University of Tsukuba, Ibaraki, Japan  
 WVII-A Wendelstein VII-A Institute for Plasma Physics, Garching, Federal Republic of Germany  
 HEL-E Heliotron E, Kyoto University, Kyoto, Japan  
 D III Doublet III, GA Technologies, Inc., San Diego, CA  
 JET Joint European Torus, JET Joint Undertaking, Abingdon, United Kingdom  
 TFTR Tokamak Fusion Test Reactor, Princeton Plasma Physics Laboratory, Princeton, NJ  
 ALC-C Alcator C, Massachusetts Institute of Technology, Cambridge, MA

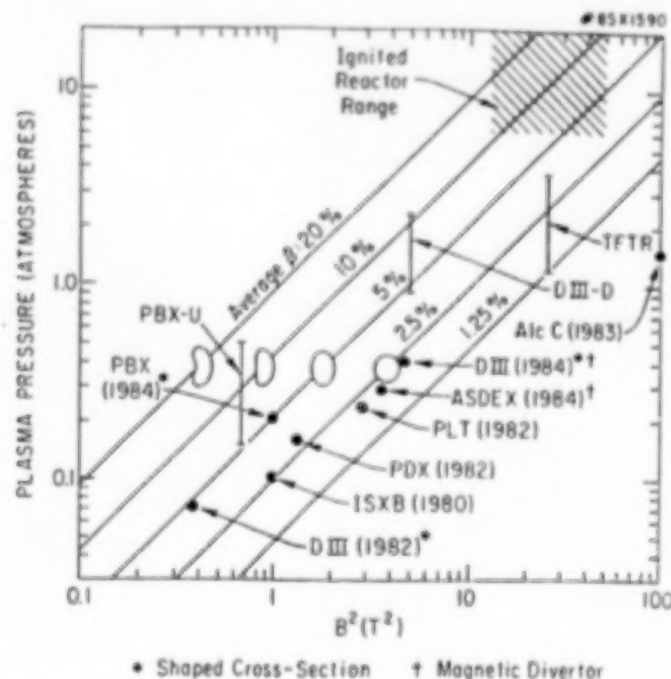
SOURCE: Office of Technology Assessment, 1987.

Figure 4-14.—Progress in Tokamak Parameters



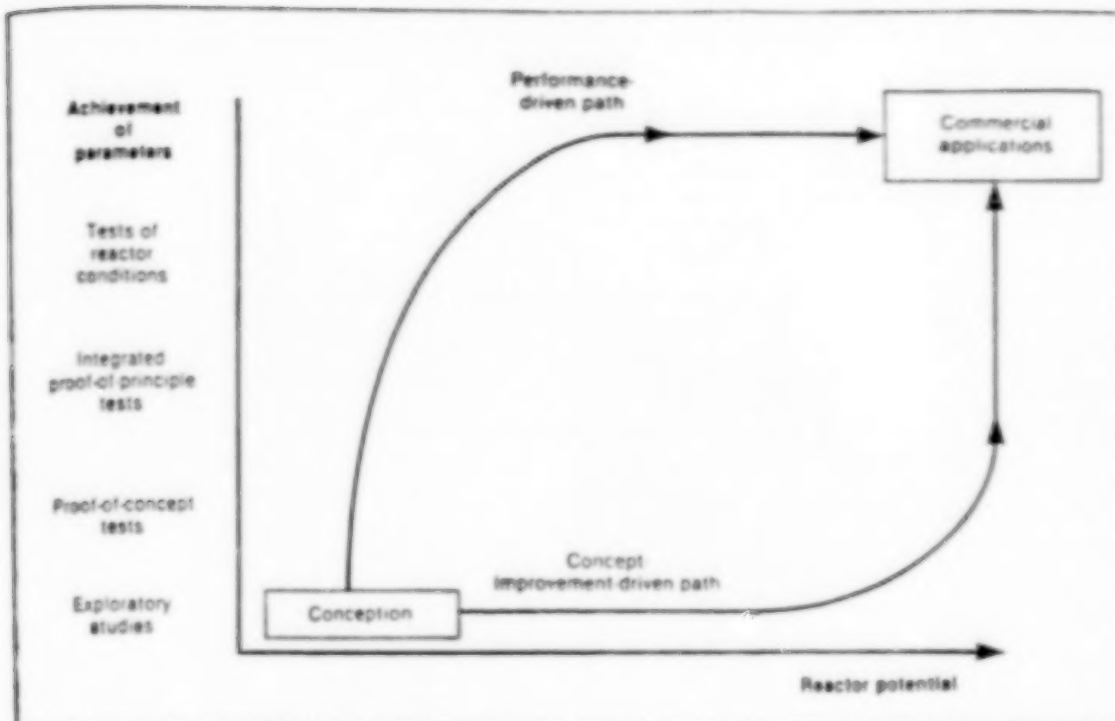
- (A)  $n_i T_i \tau_{ei}$  representing the simultaneous achievement of the three parameters—density, ion temperature, and confinement time—needed to produce fusion power
- (B)  $T_i$  = ion temperature
- (C)  $\beta$  = ratio of plasma pressure to magnetic field pressure; provides a measure of the efficiency with which the magnetic fields are used

SOURCE: Updated from National Research Council, *Physics Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986), figure 4.6: 11.



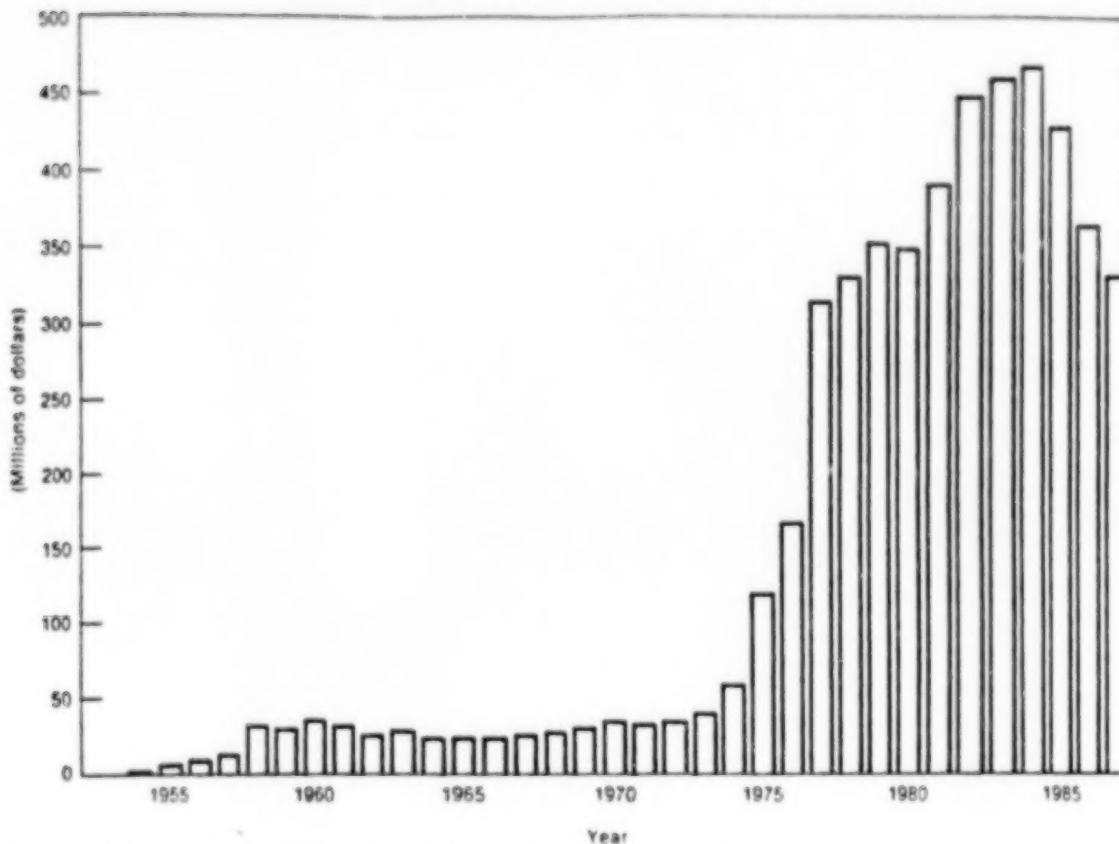
Recent progress of toroidal experiments towards the beta regime of an ignited reactor. The illustrative cross-section shapes indicate theoretical beta-limits for aspect ratios of about 3. Experimental results are mainly for near-circular cross-section tokamaks, except for DIII-D (D-shaped) and PBX (bean).

### Alternate Paths for Concept Development



SOURCE: Adapted from Argonne National Laboratory, Technical Planning Activity, Final Report, commissioned by the U.S. Department of Energy, Office of Energy Research, AN/LTRP-87-1, January 1987, figure 1.5, p. 56.

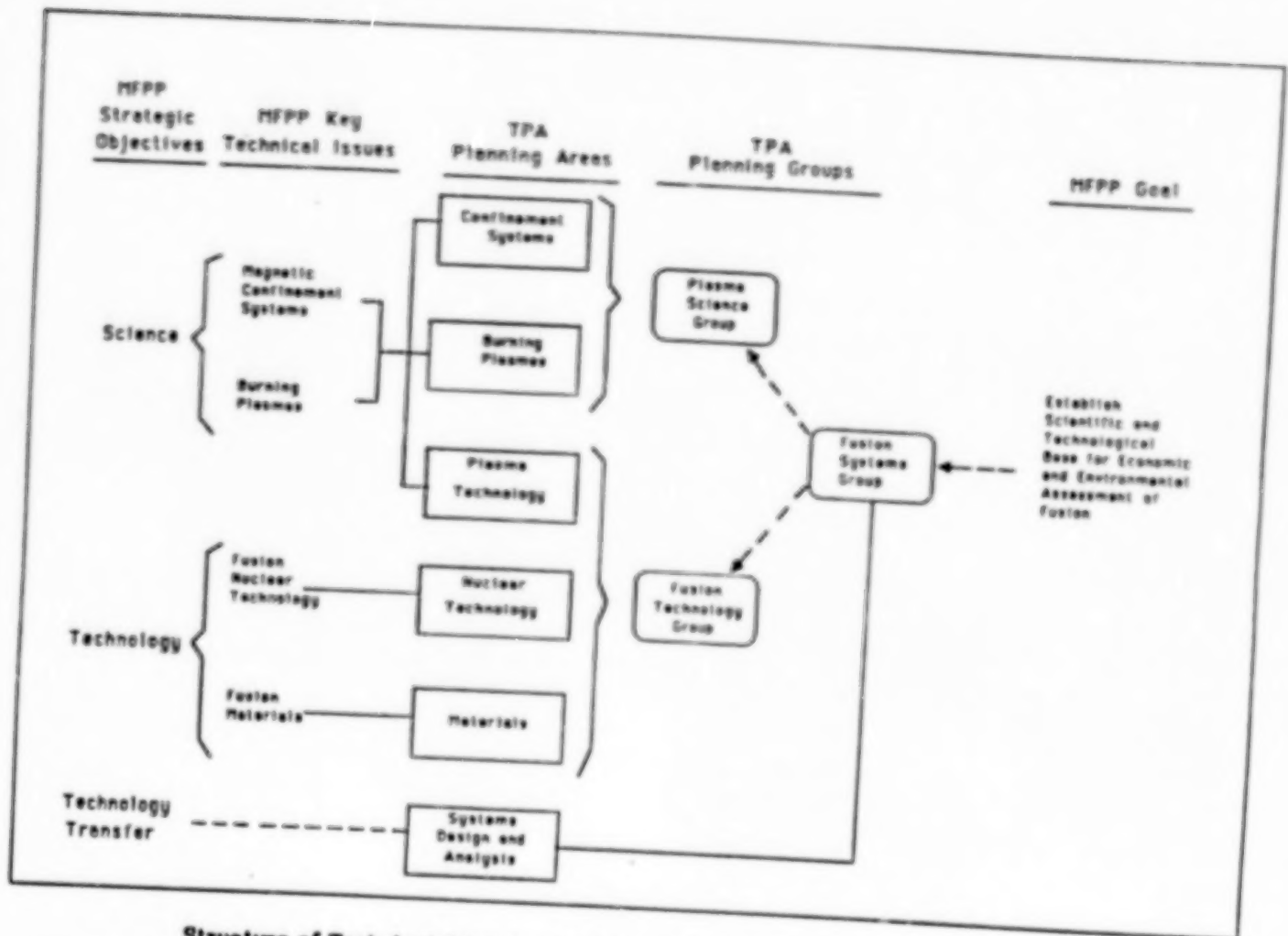
### Historical Magnetic Fusion R&D Funding, 1951-87 (in current dollars)



SOURCE: U.S. Department of Energy, Office of Energy Research, letter to OTA project staff, Aug. 15, 1986.

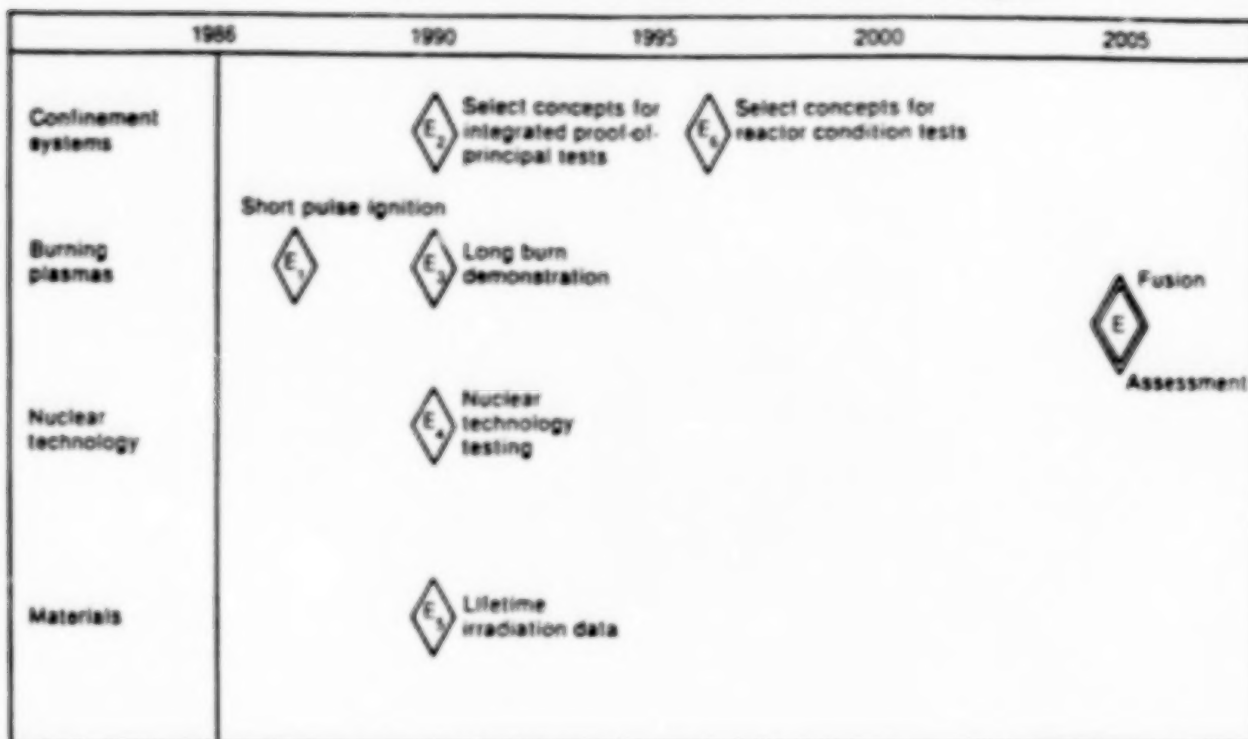


# FUTURE PLANS FOR U.S. MAGNETIC FUSION PROGRAM PLAN



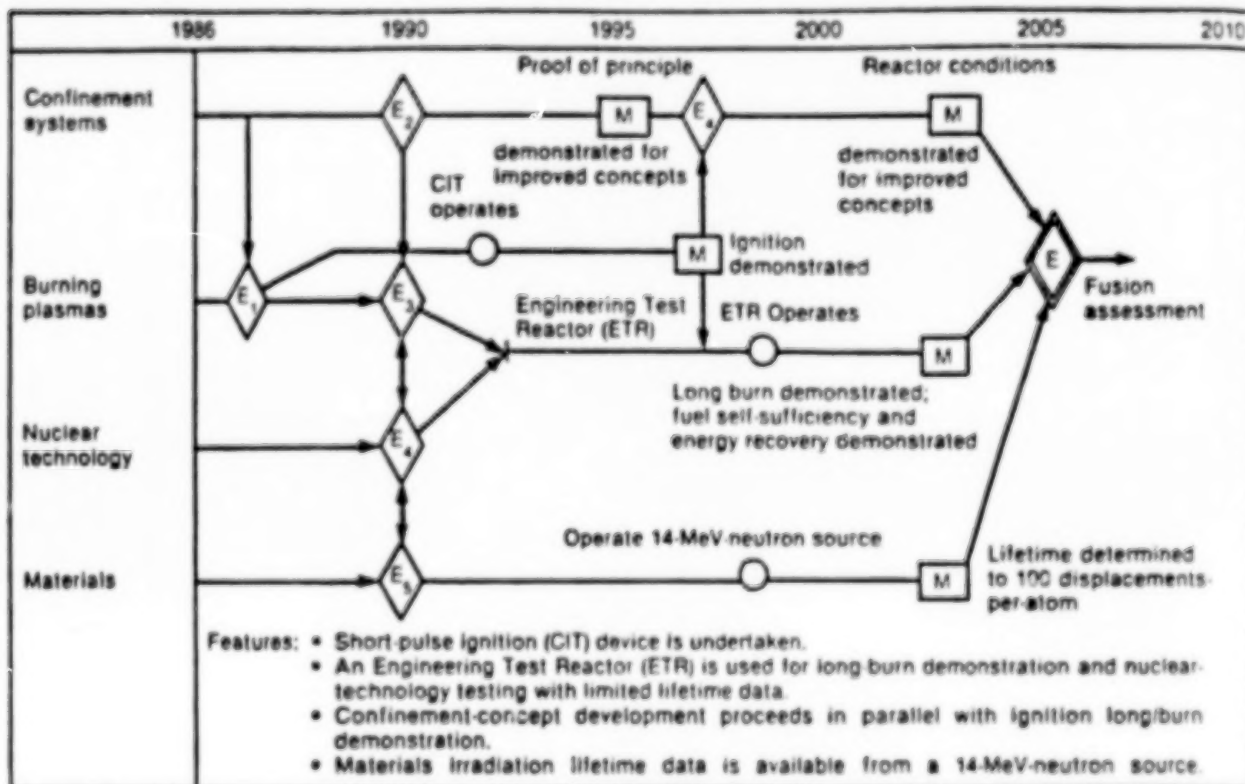
Structure of Technical Planning Activity and Its Relationship to Magnetic Fusion Program Plan

### Top Level Decision Points in the Magnetic Fusion Program



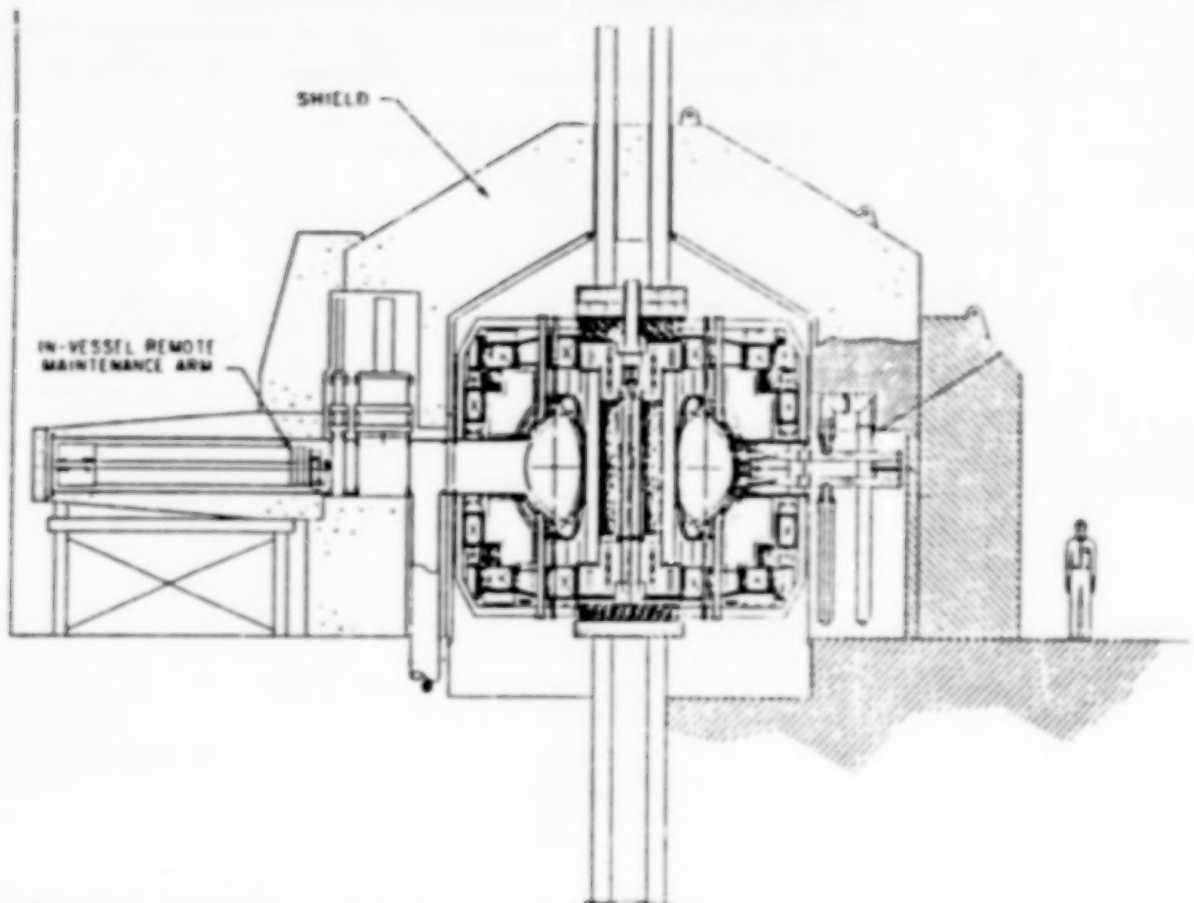
SOURCE: Argonne National Laboratory, Technical Planning Activity, Final Report, commissioned by the U.S. Department of Energy, Office of Fusion Energy, ANL/FPP-87-1, January 1987, figure 5.8, p. 23.

### Reference Scenario for the Magnetic Fusion Program



SOURCE: Argonne National Laboratory, Technical Planning Activity, Final Report, commissioned by the U.S. Department of Energy, Office of Fusion Energy, ANL/FPP-87-1, January 1987, figure 5.10, p. 27.

Preliminary CIT Design



SOURCE: Princeton Plasma Physics Laboratory, 1987

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# COMMENTS ABOUT ADVANCED FUELS IN U.S. MAGNETIC FUSION PROGRAM PLAN

## Fusion Fuel Cycles\*

Cycle	Primary reaction	Percent of energy carried by charged particles
D-T cycle	$D + T \rightarrow {}^4\text{He} + n + 17.59 \text{ million electron volts (MeV)}$ [D=deuterium; T=tritium; ${}^4\text{He}$ =alpha particle, or helium nucleus]	20% <sup>1</sup>
D-D cycle	$D + D \rightarrow p + T + 4.03 \text{ MeV}$ $D + D \rightarrow {}^3\text{He} + n + 3.27 \text{ MeV}$ [p=proton; ${}^3\text{He}$ =helium isotope with one less neutron than ${}^4\text{He}$ ]	62% <sup>2</sup>
D- ${}^3\text{He}$ cycle	$D + {}^3\text{He} \rightarrow {}^4\text{He} + p + 18.34 \text{ MeV}$	up to 98% <sup>3</sup>
D-Li cycle	$D + {}^6\text{Li} \rightarrow 5 \text{ different reactions}$ [ ${}^6\text{Li}$ =isotope of lithium]	over 65% <sup>4</sup>
p- ${}^{11}\text{B}$ cycle	$p + {}^{11}\text{B} \rightarrow {}^4\text{He} + {}^4\text{He} + {}^4\text{He} + 8.68 \text{ MeV}$ [ ${}^{11}\text{B}$ =isotope of boron]	almost 100% <sup>5</sup>

\*Presented in order of increasing difficulty, the last reaction is from 100 to 10,000 times harder to ignite than the first one, depending on temperature.

<sup>1</sup>Sixty-two percent is the fraction of the energy carried off by charged particles, assuming that the intermediate reaction products (T and  ${}^3\text{He}$  "react") with the D-T and D- ${}^3\text{He}$  reactions. With these additional reactions, the full reaction is



Twenty-eight percent can be obtained for mixtures lean in D and rich in  ${}^3\text{He}$  (see footnote 21 in main text, above).

<sup>2</sup>A low energy (0.15 MeV) neutron is produced in the secondary reaction  ${}^3\text{He} + {}^1\text{H} \rightarrow {}^4\text{He} + 0.15 \text{ MeV}$  [ ${}^1\text{H}$ =isotope of hydrogen].

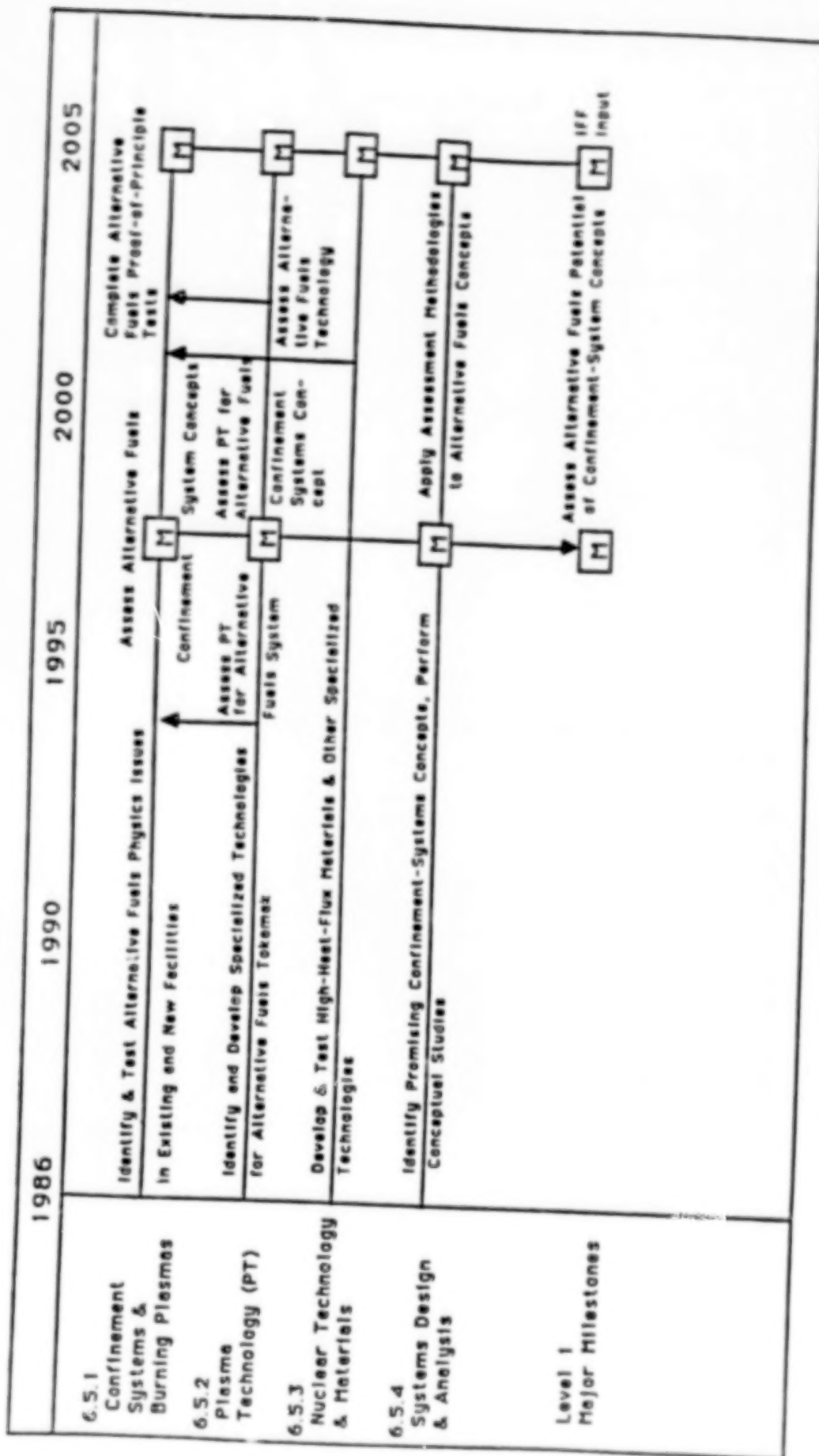
SOURCE: U.S. Department of Energy, Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy, DOE/EH-0178 August 1983, p. 2-3 (table 2-1) and pp. 2-24 to 2-27, including table 2-2.

## Objectives and Attributes for Alternative Fuels

### Program Element

Objectives	Attributes
Minimize production and handling of tritium.	Cost of tritium-handling subsystem, expressed as percent of total plant cost
Minimize production of neutrons.	Fraction of total fusion energy carried by neutrons, expressed as percent
Maximize potential for nonthermal energy conversion.	Overall plant efficiency, in percent
Maximize capability to achieve the higher beta and confinement times necessary for alternative-fuel systems.	Predictive capability of plasma theory to verify experiment

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Level 2 Logic Diagram for Alternative Fuels

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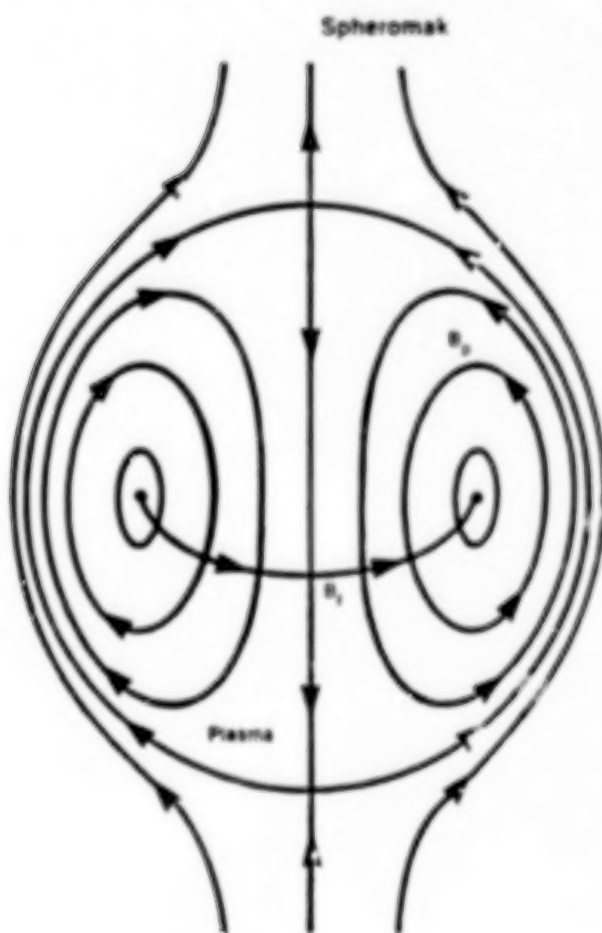
COMMENTS ABOUT ALTERNATIVE CONFINEMENT CONCEPTS WELL SUITED FOR  $D/{}^3\text{He}$   
OPERATION AND DEVELOPMENT PLANS FROM U.S. MAGNETIC FUSION

PROGRAM PLAN

Classification of Confinement Concepts

Well developed knowledge base	Moderately developed knowledge base	Developing knowledge base
Conventional Tokamak	Advanced Tokamak Tandem Mirror Stellarator Reversed Field Pinch	Spheromak Field Reversed Configuration Dense Z-Pinch

SOURCE: Adapted from Argonne National Laboratory Fusion Power Program Technical Planning Activity Final Report commissioned by the U.S. Department of Energy Office of Fusion Energy, ANL/EP-87-1, 1987, p. 15.



$B_p$  = Poloidal magnetic field

$B_t$  = Toroidal magnetic field

SOURCE: M. N. Rosenbluth and M. N. Bussac, "MHD Stability of Spheromak,"  
Nuclear Fusion 16(1):489-498 (Vienna, Austria: International Atomic  
Energy Agency, 1976).

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### Major World Spheromaks\*

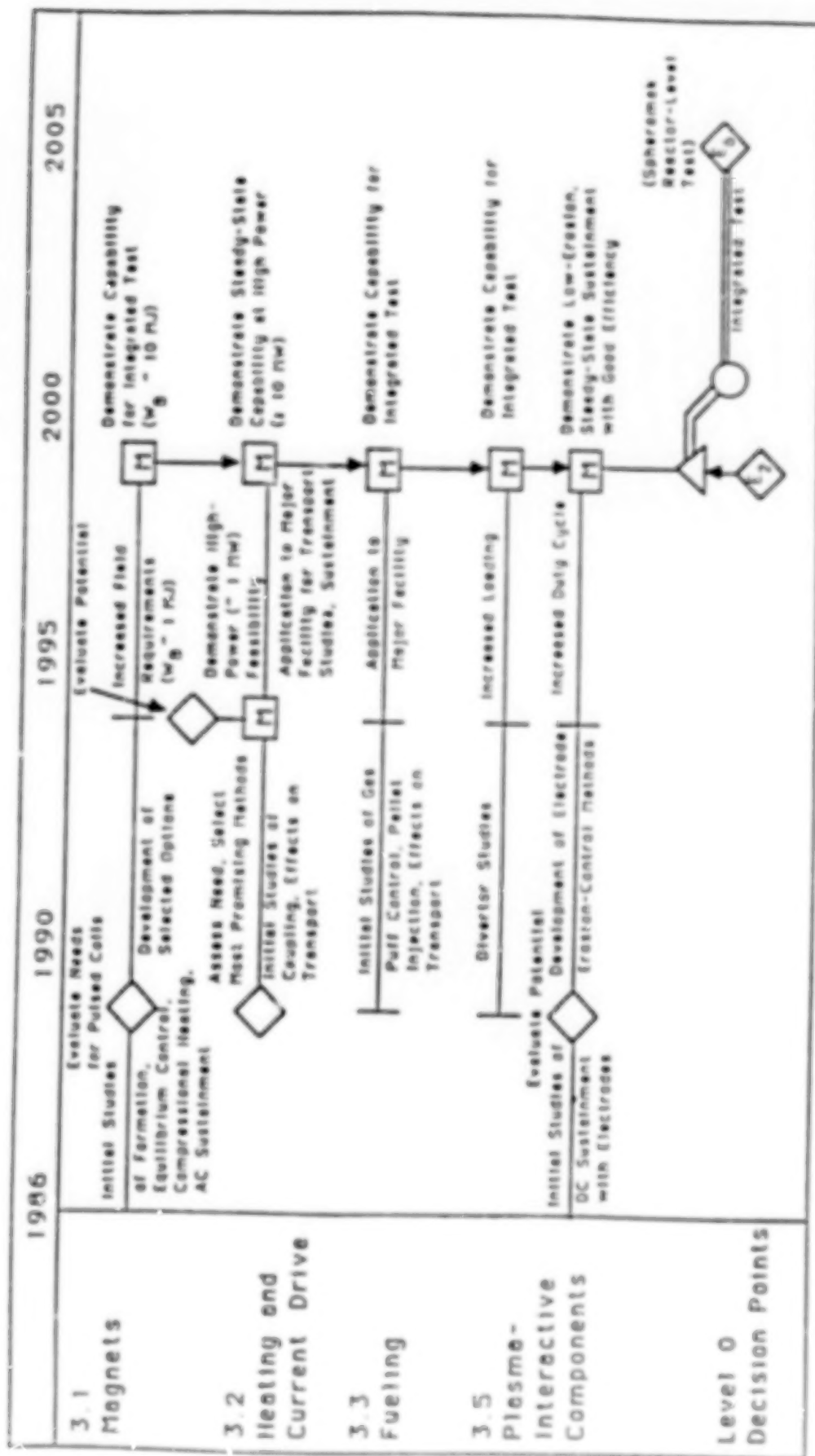
Device	Location	Status
S-1	United States (PPPL)	To be terminated, fiscal year 1988
CTX	United States (LANL)	Terminated, fiscal year 1987
MS	United States (University of Maryland)	Under construction
CTCC	Japan	Operating
Manchester U.	United Kingdom (University of Manchester)	Operating
TS-3	Japan	Operating

\*Listed approximately by decreasing order of the size of the spheromak research effort at each site. It is difficult to specify any single physical parameter as a rough measure of spheromak capability.

SOURCE: Office of Technology Assessment, 1987

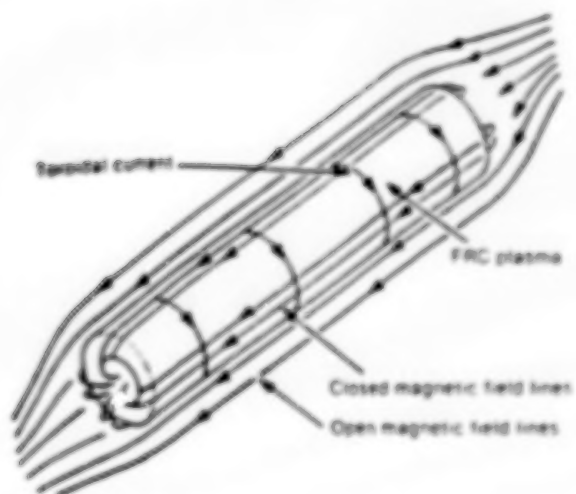
### Spheromak Program Elements, Subelements, Objectives, and Attributes

Program Elements and Subelements	Objectives	Attributes
<b>Macroscopic Equilibrium and Dynamics</b>		
Macroscopic Stability	Minimize the amount and complexity of external structures (both driven and passive) required to control equilibrium and gross tilt and shift instabilities.	Field-line symmetry and closure
Current- and Pressure-Driven Effects	Obtain q-profiles that reduce kink- and ballooning-mode effects.	$q(\rho)$ , $\langle \delta \rangle$
<b>Transport</b>		
Energy Confinement	Control the processes that determine spheromak energy loss.	$nT_E$
<b>Wave-Plasma Interactions</b>		
Wave Heating	Apply auxiliary heating or current drive by efficient rf techniques, as required.	Source-to-spheromak efficiency
<b>Particle-Plasma Interactions</b>		
Impurity Control	Reduce impurity effects through combined ohmic-heating, burn-through and divertor action of open magnetic flux.	$Z_{eff}$
<b>Composite</b>		
Pulse-Length Optimization	Develop methods for sustainment against resistive decay, based on helicity injection or current drive.	Efficiency, $t_{pulse}^{1/2} R$



Level 3 Logic Diagram for Spheromak Plasma Technology

### Field-Reversed Configuration



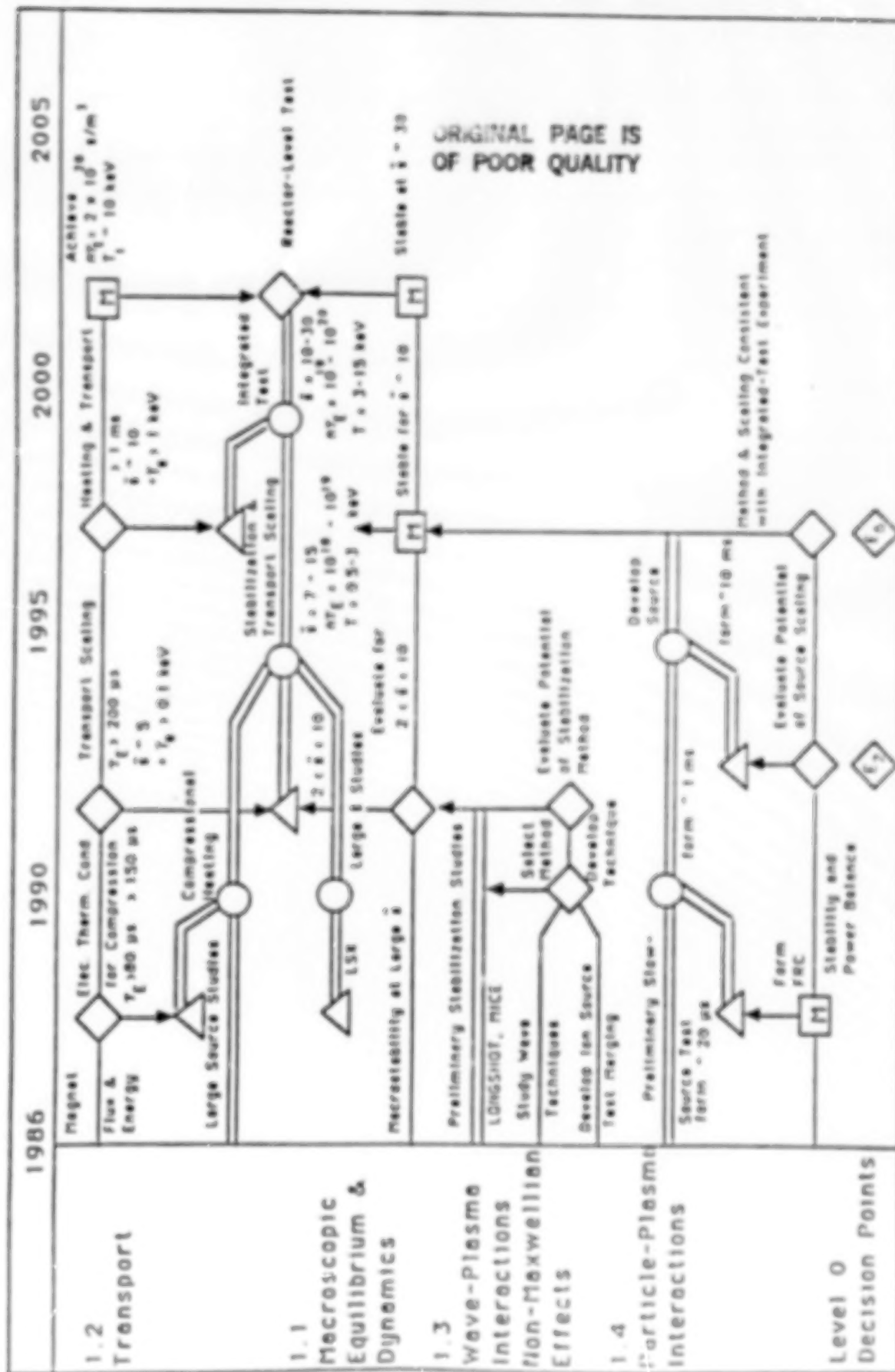
SOURCE: National Research Council, *Physics Through the 1990s: Plasmas and Fluids* (Washington, DC: National Academy Press, 1986).

### Major World Field-Reversed Configurations\*

Device	Location	Status
LSX .....	United States (Spectra Technologies)	Under construction
FRX-C .....	United States (LANL)	Operating
BN, TOR .....	U.S.S.R. (Kurchatov)	Operating
TRX-2 .....	United States (Spectra Technologies)	Operating
OCT, FIACE .....	Japan (Osaka University)	Operating
NUCTE .....	Japan (Nihon University)	Operating

\*Listed approximately by decreasing order of size; similarly sized devices at the same facility are listed together.

SOURCE: Office of Technology Assessment, 1987, from information supplied by the Los Alamos National Laboratory.



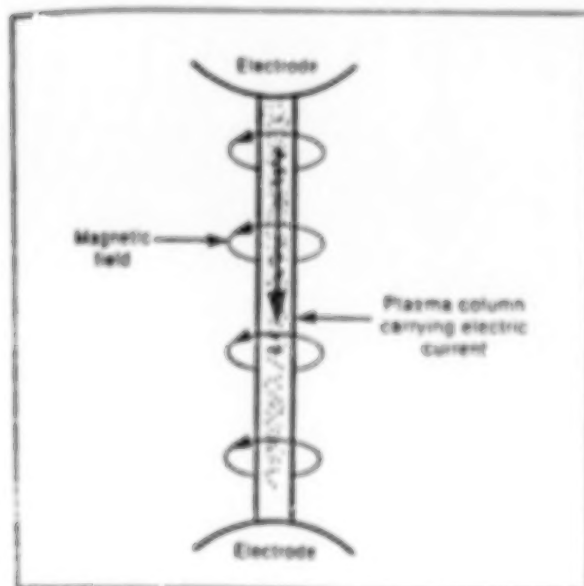
Level 2 Logic Diagram for the Field-Reversed Configuration



# Field-Reversed Configuration Program Elements, Subelements, Objectives, and Attributes

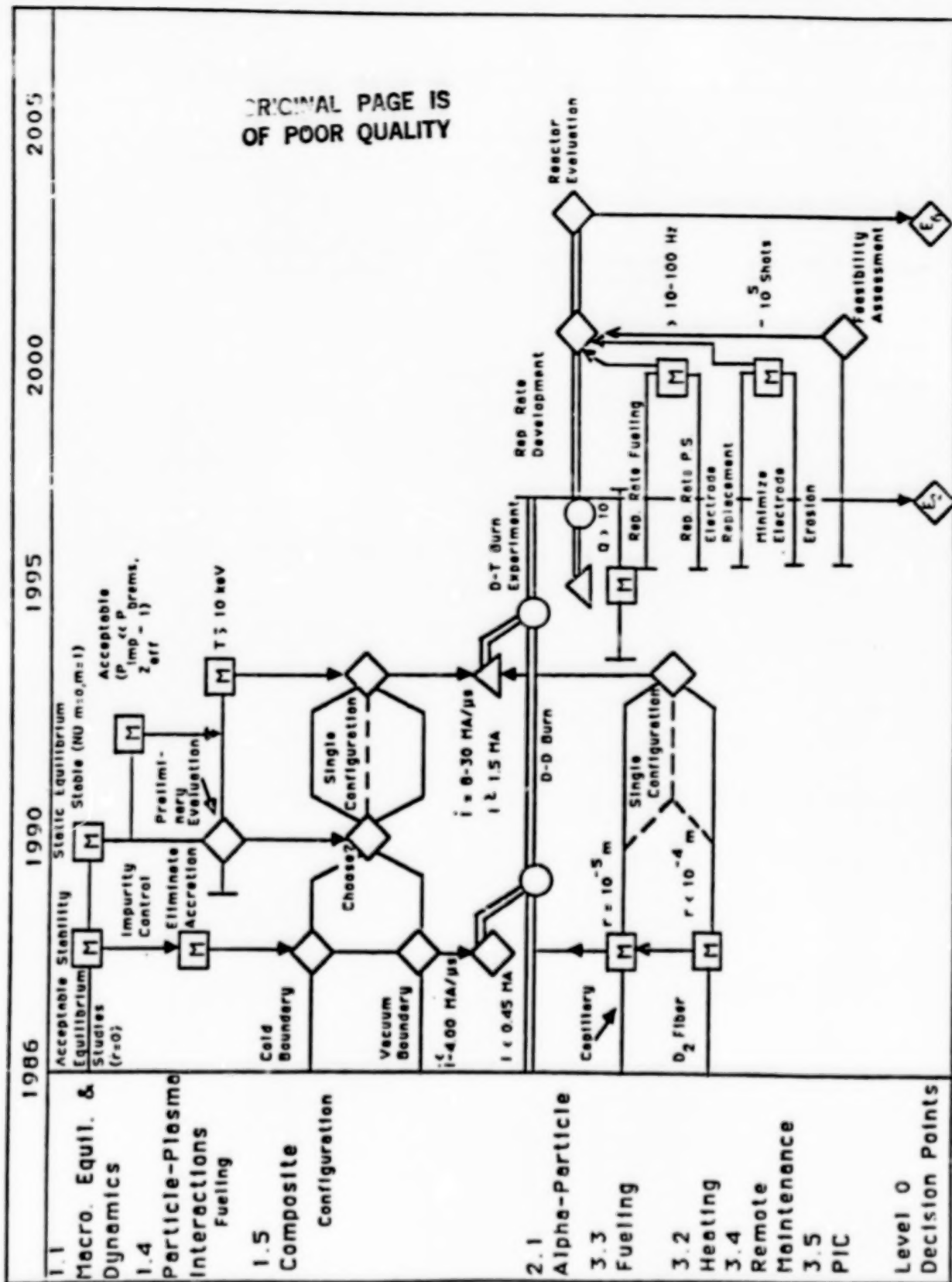
Program Elements and Subelements	Objectives	Attributes
Macroscopic Equilibrium and Dynamics		
MHD Equilibrium and Stability	Maintain stability with increased $\bar{s}$ .	Value of $\bar{s}$
Transport		
Energy Confinement	Demonstrate favorable scaling of energy confinement with $\bar{s}$ .	$\tau_E(\bar{s})$
Heating	Establish adiabatic compression as viable method.	$\tau_E(\text{Temp.})$
Composite		
Formation	Develop lower-voltage formation method.	$\tau_f$ , formation timescale

Dense Z-Pinch



LA-5000 Office of Technology Assessment 1967

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Level 2 Logic Diagram for Denze % Pinch

Program Elements, Subelements, Objectives, and Attributes for the  
Dense Z-Pinch

Program Elements and Subelements	Objectives	Attributes
<b>Macroscopic Equilibrium and Dynamics</b>		
Magnetic Transients	Demonstrate stable equilibrium at $I \geq 1.4$ MA.	No gross instability during current rise
<b>Transport</b>		
Energy Confinement	Demonstrate reactor-level confinement.	$n\tau_E$
<b>Particle-Plasma Interactions</b>		
Fueling	Eliminate accretion.	$\dot{N} = 0$ rep rate in Hz
	Reactor-relevant repetition rate.	Repetition rate in Hz
Alpha-Particle Effects	Minimize core plasma heating; minimize exo-column ionization and current diversion; and understand alpha-particle/electrode interaction.	Frequency/mass/cost of electrode replacement
Radiative Collapse of Pinch	Understand dynamics Enhance fuel burning.	DT burnup
Composite	Choose configuration (cold boundary vs. vacuum boundary).	$Z_{eff}, \tau_E$

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## Dense Z-Pinch Decision on Proceeding with DD Burn Experiment

### Statement of Decision

To proceed with the DD burn experiment, in which the primary objective is to obtain equivalent DT  $Q > 1$ .

### Decision Criteria

Obtain stable, static equilibria at the 1.5-MA current level.  
Explore confinement scaling for  $n_E = 10^{17}$ - $10^{18}$  s/m<sup>3</sup>.  
Choose between cold-boundary and vacuum-boundary approaches on the basis of preliminary transport, stability, and impurity-level assessments.

### Sources of Information

Results from existing dense Z-pinch experiments.  
Preliminary results from dense Z-pinch DD burn experiments.  
Plasma supporting activities (principally in Europe).

### Outcomes and Consequences of Decision

Favorable assessment and achievement of the objectives of the DD burn experiments would lead to a DT burn experiment and an assessment of the technological possibilities of developing the concept towards a reactor (particularly with respect to the repetition-rate problem).  
Undertake further research to resolve the remaining issues.  
Terminate the dense Z-pinch program.

## Cost of Representative Fusion Experiments

Experiment	Location	Type	Construction cost (millions of 1987 dollars)
Tokamak Facility Test Reactor	PPPL	Tokamak	\$562
Mirror Fusion Test Facility-B	LLNL	Tandem Mirror	\$330
Doublet III	GA	Tokamak	\$ 56 <sup>a</sup>
Doublet III-D (Upgrade)	GA	Tokamak	\$ 36 <sup>a</sup>
International Fusion Superconducting Magnet Test Facility	ORNL	Magnet Test <sup>b</sup>	\$ 36 <sup>c</sup>
Poloidal Divertor Experiment	PPPL	Tokamak	\$ 54
Princeton Large Torus	PPPL	Tokamak	\$ 43
Tritium Systems Test Assembly	LANL	Tritium Test <sup>b</sup>	\$ 26
Tandem Mirror Experiment	LLNL	Tandem Mirror	\$ 24
Tandem Mirror Experiment Upgrade	LLNL	Tandem Mirror	\$ 23
Texas Experimental Tokamak	UT	Tokamak	\$ 21
Advanced Toroidal Facility	ORNL	Stellarator	\$ 21
TARA	MIT	Tandem Mirror	\$ 19
ZT-40	LANL	Reversed-Field Pinch	\$ 17
Alcator C	MIT	Tokamak	\$ 15
Rotating Target Neutron Source	LLNL	Materials Test <sup>b</sup>	\$ 11
Impurity Studies Experiment-B	ORNL	Tokamak	\$ 5
Field Reversed Experiment-C	LANL	Field-Reversed Configuration	\$ 3
Phaedrus	UW	Tandem Mirror	\$ 1.8
MacroTOR	UCLA	Tokamak	\$ 1.5
IMS	UW	Stellarator	\$ 1.4
Tokado18	UW	Tokamak	\$ 0.6

KEY: PPPL—Princeton Plasma Physics Laboratory, Princeton, New Jersey  
LLNL—Lawrence Livermore National Laboratory, Livermore, California  
ORNL—Oak Ridge National Laboratory, Oak Ridge, Tennessee  
GA—GA Technologies, Inc., San Diego, California  
LANL—Los Alamos National Laboratory, Los Alamos, New Mexico  
UT—University of Texas, Austin, Texas  
MIT—Massachusetts Institute of Technology, Cambridge, Massachusetts  
UW—University of Wisconsin, Madison, Wisconsin  
UCLA—University of California, Los Angeles, California

<sup>a</sup>Values shown for the combined Doublet III facility and upgrade do not include an additional \$54 million (in current dollars) of hardware provided by the government of Japan or \$36 million (in 1987 dollars) for a neutral beam addition.

<sup>b</sup>These facilities are fusion technology facilities, all others on the table are confinement physics experiments.

<sup>c</sup>The cost of this facility does not include the cost of the six magnet coils that are being tested there. It is estimated that the magnet coils cost between \$12 million and \$15 million each (in current dollars).

SOURCE: U.S. Department of Energy, Office of Fusion Energy, 1987.

## EXAMPLE OF HIGH TEMPERATURE D/<sup>3</sup>He BURN EXPERIMENT

### OBJECTIVES OF HI-T EXPERIMENT

- OBTAIN PLASMA SCALING DATA AT 30 TO 40 keV OF INTEREST TO D-BASED ADVANCED FUELS
- DEMONSTRATE ADVANCED FUEL BURN BY REFUELING TO CONVERT FROM D-T TO D/<sup>3</sup>He

### APPROACH

- USE D-T THERMAL RUN-AWAY IN HIGH- $\beta$  RFTP

### RFOP BURN DYNAMIC EXPERIMENT

#### NEUTRAL BEAM/PELLET INJECTION INTO RFTP

- PROVIDES AUXILIARY HEATING BEYOND COMPRESSION/SHOCK
- PROVIDES FUELING  $50\tau_{\text{BURN}} \sim 5\tau_{\text{PARTICLE}}$
- COUNTER-DIRECTED BEAM SUPPRESSES ROTATION
- DENSITY PROFILE CONTROL SUPPRESSES LOWER HYBRID DRIFT

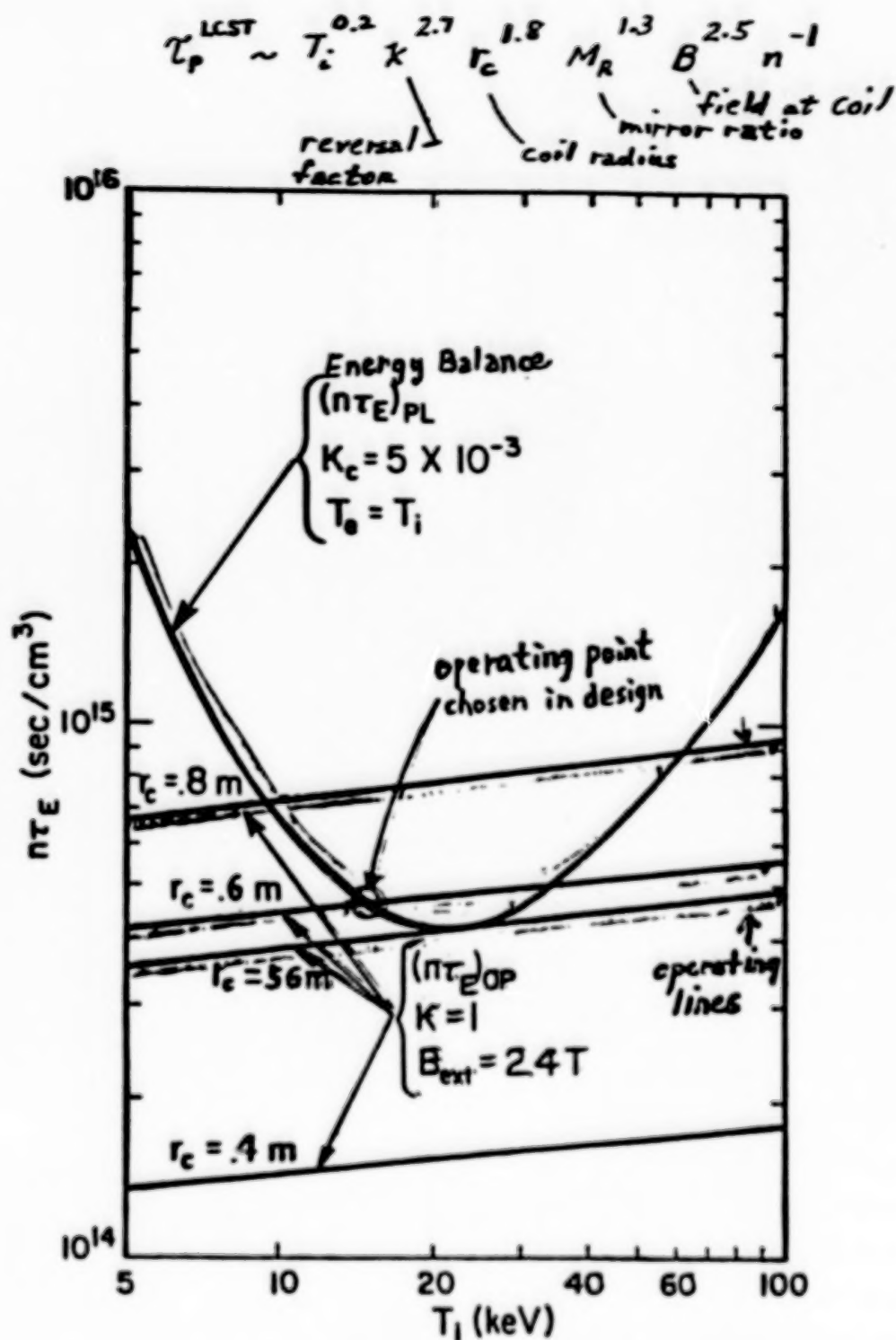
#### WHY RFTP?

- HIGH  $\beta$
- EXPERIMENTAL DATA PROMISING
- LSST SCALING SUPPORTS FEASIBILITY OF HIGH-T OPERATION
- COMPACT SIZE ALLOWS RAPID CONSTRUCTION AT MODEST COST
- ALLOWS ADVANCED FUELS

#### KEY PROBLEMS

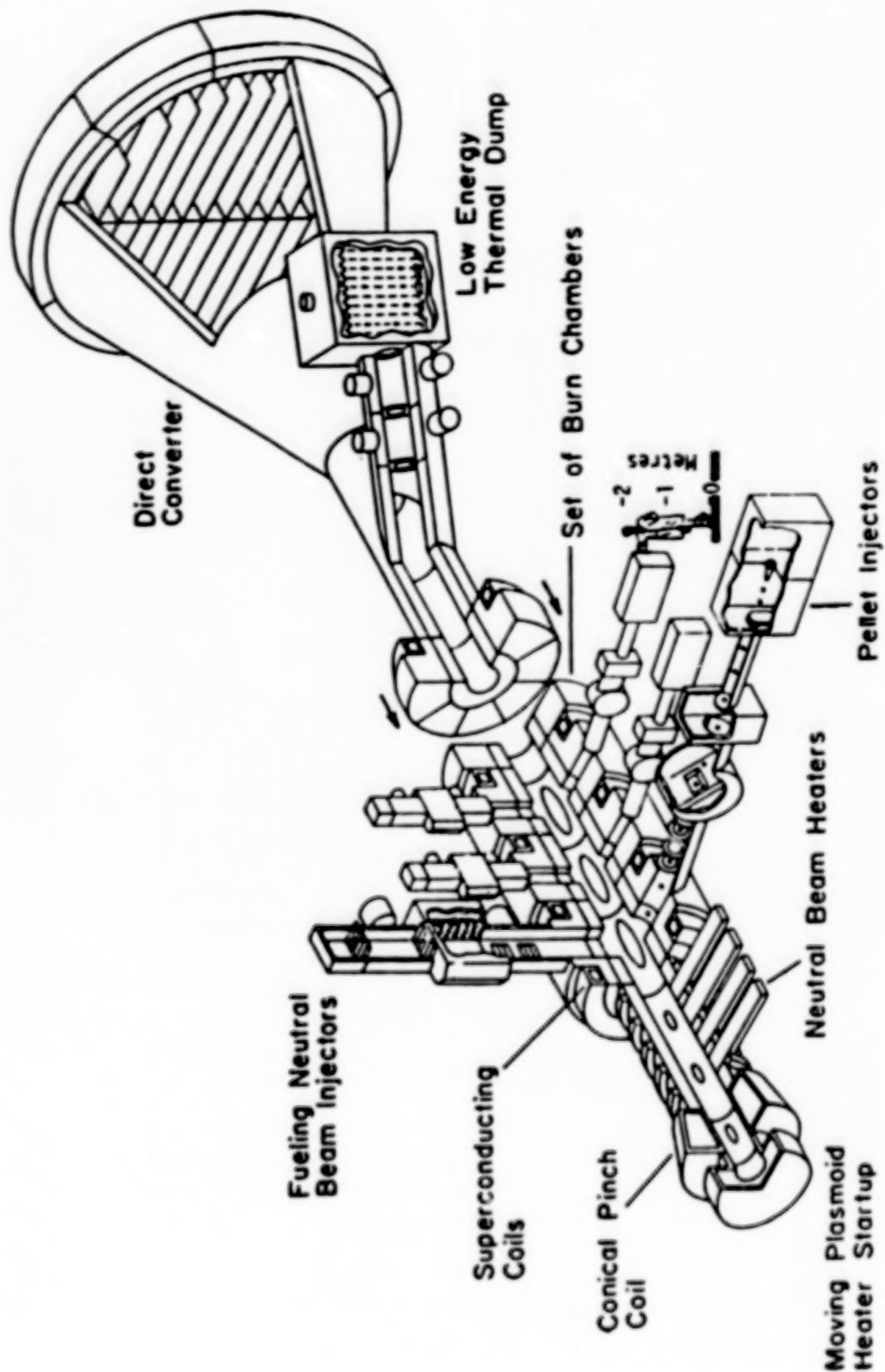
- SUPPRESS PLASMA SPIN-UP
- SUPPRESS STEP DENSITY GRADIENTS CAUSING LOW HYBRID DRIFT INSTABILITY

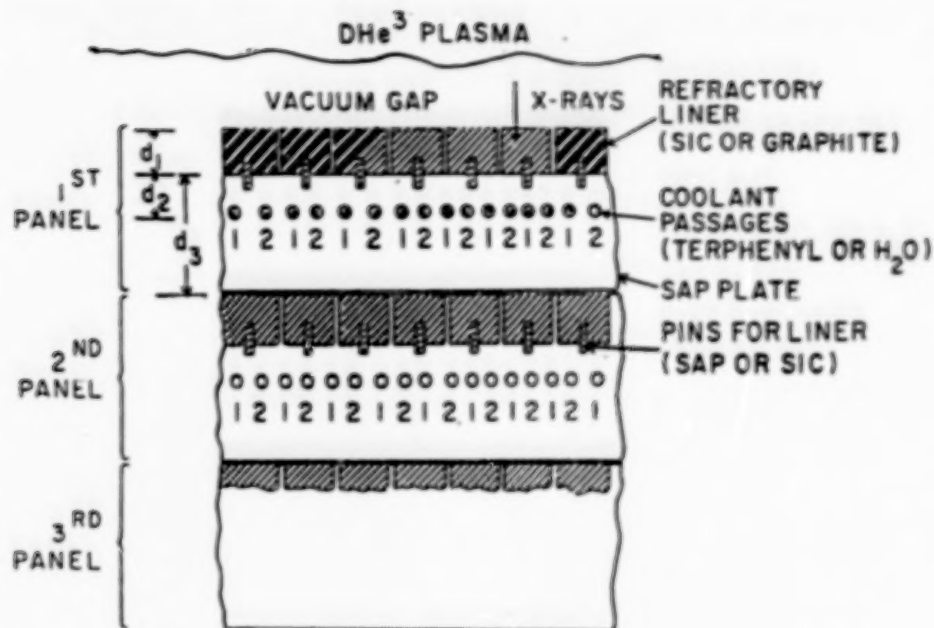




$(n\tau_E)_{OP}$  and  $(n\tau_E)_{PL}$  versus  $T_i$  for a D-T system.  
 Here  $(n\tau_E)_{OP}$  is based on the "loss-cone-like" scattering  
 transport model (see reference), where  $K$  is the  
 field reversal factor.

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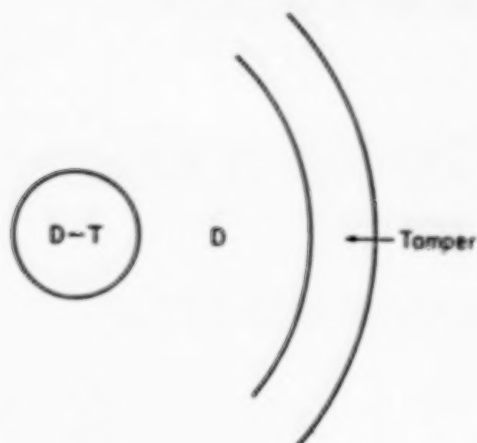
ALUMINUM BLANKETS FOR DHe<sup>3</sup> REACTORS CROSS SECTION

## SAFFIRE

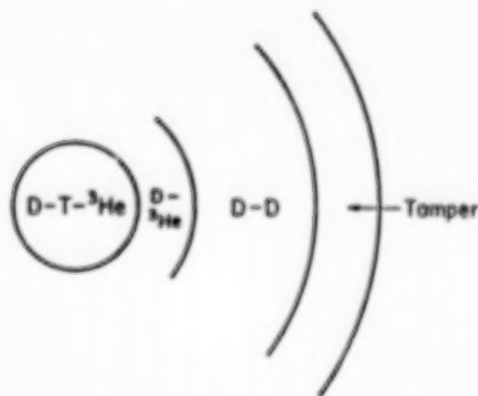
Power	Split, %
plasma	0.39
fp	0.37
radiation	0.22
neutrons	0.02
	0.76

# CONCEPTS FOR BURNING ADVANCED FUELS WITH INERTIAL CONFINEMENT USING A-FLINT CONCEPT

[Burn propagation ignited by a D-T central spark.]

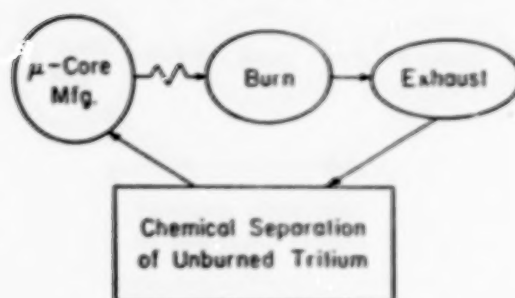


THE A-FLINT TARGET CONCEPT USES BURN PROPAGATION TO IGNITE AN  
OUTER DEUTERIUM LAYER. A MAIN OBJECTIVE IS TO PROVIDE  
TRITIUM BREEDING IN THE TARGET (VIA D-D REACTIONS) SO THAT  
THE BLANKET NEED NOT BREED.



THE BURN PROPAGATION IS IMPROVED BY USE OF <sup>3</sup>He (BREED INTERNALLY  
BY D-D ALSO). IN THIS FIGURE AN OPTIMUM ARRANGEMENT IS SHOWN.

# TRITIUM SELF SUFFICIENCY



FLOW DIAGRAM FOR TRITIUM WHEREBY TRITIUM PRODUCED BY D-D REACTIONS IN THE BURN IS USED TO MANUFACTURE SUBSEQUENT D-T MICRO-CORES. A TARGET TRITIUM BREEDING RATIO (TBR) SLIGHTLY GREATER THAN 1.0 IS REQUIRED FOR SELF SUFFICIENCY, I.E., ELIMINATE THE NEED FOR A LITHIUM BREEDING BLANKET.

## Prior D-Based Pellet Studies

REFERENCE	TYPE	$E_i$ (MJ)	$\epsilon$ (J/gm)	$q_F$ (gm-cm <sup>-2</sup> )	TBR	G
WOOD, Ref. 8	Cat. D Burner (T; <sup>3</sup> He Seed)	2-10	?	?	> 1.0	1/2xDT
HUCKO LS, Ref. 5	Cat. D Burner (T; <sup>3</sup> He Seed)	10	$3 \times 10^7$	?	> 1.0	?
MOSES, Ref. 7	Pure D Spark	> 100	$1.5 \times 10^9$	40-80		200-300
SKUPSKY, Ref. 10	50/50 D-T Spark; 90/10 Outside	0.16 abs.	$1.6 \times 10^8$	25	0.4	580
1978 A-FLINT, Refs. 12-14	50/50 D-T Spark; Pure D Outside	1.8 abs.	$9.7 \times 10^7$	13	1.1	1700
1980 A-FLINT Ref. 1	*	0.1 abs.	$5.87 \times 10^7$	6.8	1.0	700

$E_i$  = input energy  
 $\epsilon$  = specific absorbed energy  
 TBR = tritium breeding ratio  
 G = gain on absorbed energy



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STRATEGY FOR D-<sup>3</sup>He FUSION DEVELOPMENT

John F. Santarius  
Fusion Technology Institute  
University of Wisconsin - Madison  
Madison, WI 53706

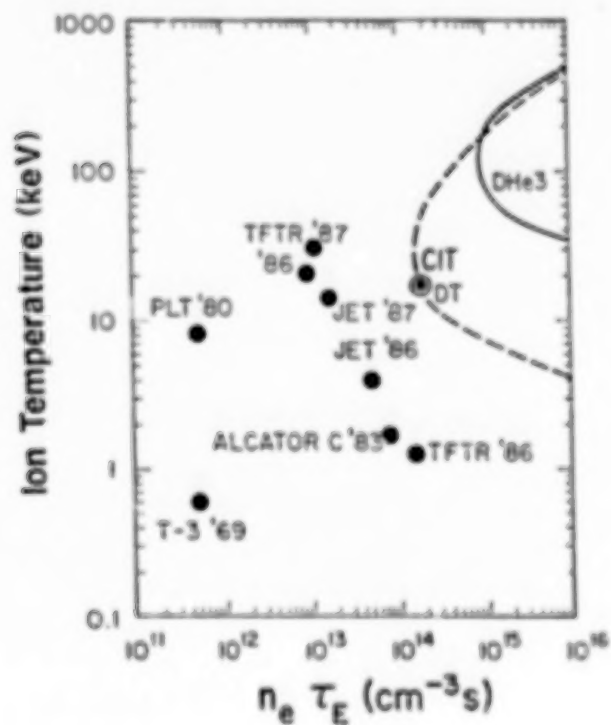
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### *Issues for D-<sup>3</sup>He Fusion Development*

- Physics
- Fueling
- Power Density
- First Wall Heat Flux
- Materials
- Plasma Heating
- Current Drive
- High-Efficiency Operation
- Safety
- Environment
- Licensing

### *Progress Toward Fusion Ignition Conditions*



### *Plasma Fueling is More Difficult For D-<sup>3</sup>He Fusion Reactors*

---

- Fuel pellets ablate more quickly in hotter plasmas and pellet fabrication is difficult
- Fueling by plasma injection appears to be a very promising option
  - Marshal can plasma fueling was done successfully on Tokapole II
  - Compact toroid fueling (proposed for U.S. ITER/TIBER) allows injection velocities of 100's of km/s
- Neutral beam fueling is also an option

### *Power Density Should be Measured in $kWe/kg$ not in $kW_{fus}/V_{plasma}$*

---

- Traditional power density arguments based on  $\beta^2 B^4$  scaling are only very rough indicators of performance
- Reduced neutron flux helps greatly
  - Reduced shield thickness and mass
  - Reduced magnet size and mass
  - Increased B field at plasma
- Direct conversion increases net electric power
- Many configurations can increase B fields in the fusion core

<u>HARD</u>	<u>MODERATE</u>	<u>EASY</u>
S/C Tokamak	Copper Tokamak	RFP
Stellarator	Heliotron	FRC
Torsatron		Tandem Mirror
		Spheromak
		EBT

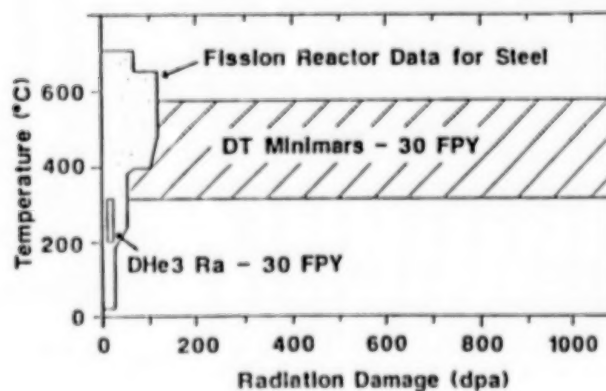
### *Increased Heat Fluxes for D-<sup>3</sup>He Reactor First Walls are Manageable*

- Zeroth order increase in heat flux is a factor of five
- Reduced neutron shielding allows larger first wall radius and area
- Present conceptual DT tokamak reactors are designed well below technologically allowable heat flux limits ( $\sim 4 \text{ MW/m}^2$ )
  - Ratio of approximate technological limit to reactor design point:

<u>DESIGN</u>	<u>RATIO</u>
STARFIRE	4.4
NUWMAK	3.6

### *Materials Suitable for D-<sup>3</sup>He Reactors Have Already Been Tested*

- The fission reactor program has provided ample data on neutron damage to materials in the range of temperatures and fluences required for a D-<sup>3</sup>He fusion reactor





*D-<sup>3</sup>He Plasma Heating is Similar  
to D-T Plasma Heating in Difficulty*

---

- Ion Cyclotron Range of Frequencies (ICRF) heating of <sup>3</sup>He has been successfully demonstrated on JET
  - Produced 50 kW of D-<sup>3</sup>He thermonuclear fusion power
  - Average <sup>3</sup>He energy rose to 200-500 keV (minority heating mode, D background)
- Electron Cyclotron Range of Frequencies (ECRF) heating requires the same technology
- Higher D-<sup>3</sup>He plasma temperatures will lead to somewhat higher neutral beam energy requirements
- Adiabatic compression should be easier because the plasma will be hotter and more ideal (in an MHD sense)

*Current Drive Physics and Technology  
Must be Better Understood before  
Judging with Respect to D-<sup>3</sup>He Fusion*

---

- Higher electron temperatures for D-<sup>3</sup>He make current drive easier
- D-<sup>3</sup>He fusion probably requires larger plasma currents
- Current drive by synchrotron radiation is easier for D-<sup>3</sup>He reactors

### *Direct Conversion to Electricity Should Be Vigorously Pursued*

---

- Potential net plant efficiencies of 70%
- Electrostatic direct conversion
  - Periodically focussed
  - Venetian blind
- Electromagnetic direct conversion
  - Adiabatic compression/decompression cycles
  - Synchrotron radiation conversion using rectennas
- Very high temperature thermal cycles
  - MHD conversion
  - Radiation boiler
  - Synfuel production

### *Utilities Want Ease of Licensing*

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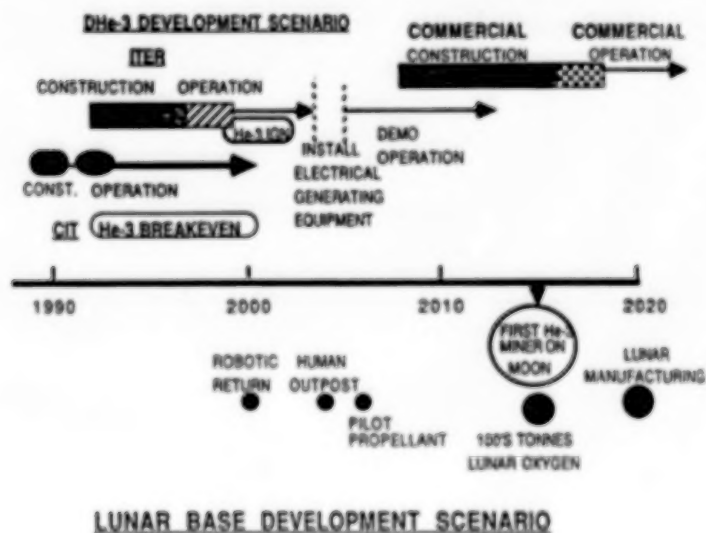
- Utility and Industry fusion advisory committees repeatedly stress that safety, environment, protection of investment, and licensing should be major thrusts of fusion power development
- D-<sup>3</sup>He fusion will assure:
  - Safety because of the low radioactive volatile inventory
  - Environmental quality because only very low-level (Class A) wastes will remain at end of reactor life
  - Protection of investment due to low afterheat (no meltdown even a month after shutdown under adiabatic conditions)
  - Ease of licensing because a D-<sup>3</sup>He fusion reactor will truly be inherently safe

## *D-<sup>3</sup>He Fusion Development Requires Harder Physics But Easier Technology*

### D-<sup>3</sup>He Physics and Technology Versus D-T

• Physics	Somewhat harder
• Fueling	Harder
• Mass Power Density	Nearly equal
• First Wall Heat Flux	Manageable
• Materials	Much easier
• Plasma Heating	Similar
• Current Drive	Similar
• High-Efficiency Operation	Much easier
• Safety	Much easier
• Environment	Much easier
• Licensing	Very much easier

## *D-<sup>3</sup>He Fusion and Lunar <sup>3</sup>He Procurement Could Occur on a Consistent Timescale*



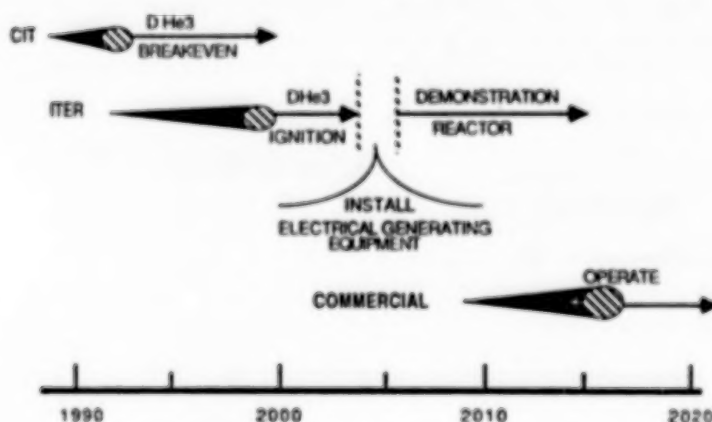
## Strategy for D-<sup>3</sup>He Fusion Development

### D-<sup>3</sup>He TOKAMAK DEVELOPMENT PATH

- 1) CIT (Compact Ignition Tokamak): Design planned D-T device to achieve D-<sup>3</sup>He  $Q \geq 2$  in an early phase of operation
- 2) ITER (International Tokamak Experimental Reactor): Design planned D-T device to achieve D-<sup>3</sup>He ignition in an early phase of operation
- 3) DEMO (Demonstration Reactor): Add power conversion and other systems to ITER in a follow-on stage to demonstrate D-<sup>3</sup>He commercial reactor viability

## D-<sup>3</sup>He Fusion Development Requires Harder Physics But Easier Technology

### D-He3 DEVELOPMENT SCENARIO



## *Strategy for D-<sup>3</sup>He Fusion Development*

---

### HIGH-LEVERAGE D-<sup>3</sup>He CONCEPTS PATH

- 1) Investigate whether a D-<sup>3</sup>He operation phase in presently planned major experiments would provide significant information
- 2) Investigate the feasibility and cost of a D-<sup>3</sup>He ignition (high-Q) experiment
- 3) Quantify advantages and disadvantages of the D-<sup>3</sup>He reactor embodiment of candidate, high-leverage concepts



**Tokamak Plasma Power Balance Computer Code**  
**Prof. G.A. Emmert**

---

Ingredients of the model:

- 1) Charged Particle Heating - a fraction of the fusion power goes to the ions; based on slowing down theory from the Fokker-Planck equation
- 2) Fast Ion Pressure
- 3) Bremsstrahlung - with relativistic corrections
- 4) Synchrotron Radiation - uses Trubnikov's "universal" formula
- 5) Energy transport across the magnetic field - uses empirical formulas for  $\tau_E$ : Kaye-Goldston or ASDEX H-Mode
- 6) Electron-Ion Energy Transfer - classical + relativistic corrections
- 7) MHD Limits - uses the Troyon  $\beta_*$  formula
- 8) Particle Confinement - Ash accumulation

$$\tau_p = \tau_E$$

- 9) Density and temperature profiles are legislated

$$n \sim (1 - r^2/a^2)^{0.8}$$

$$T \sim (1 - r^2/a^2)^{0.7}$$

It does not include:

- 1) 2 component mode of operation -  $\langle \sigma v \rangle$  is Maxwellian averaged
- 2) Impurities other than the fusion produced ash
- 3) Current drive considerations

The code calculates the ignition margin,  $M$ ,

$$M = \frac{P_{\text{FUSION}}}{\sum P_{\text{LOSSES}}}$$

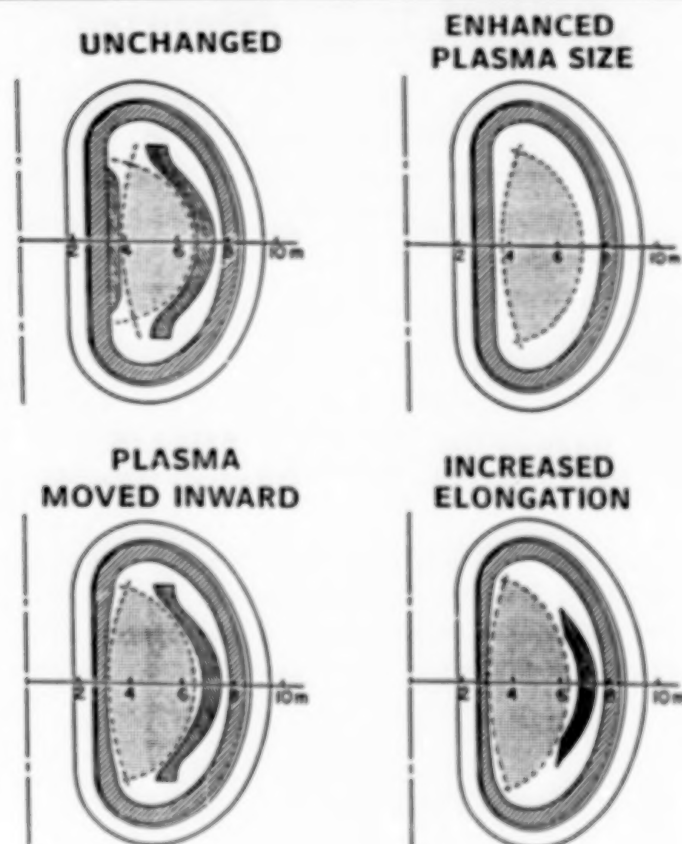
and the energy multiplication,

$$Q = \frac{P_{\text{FUSION}}}{P_{\text{inj}}} = \frac{M}{1 - M}$$

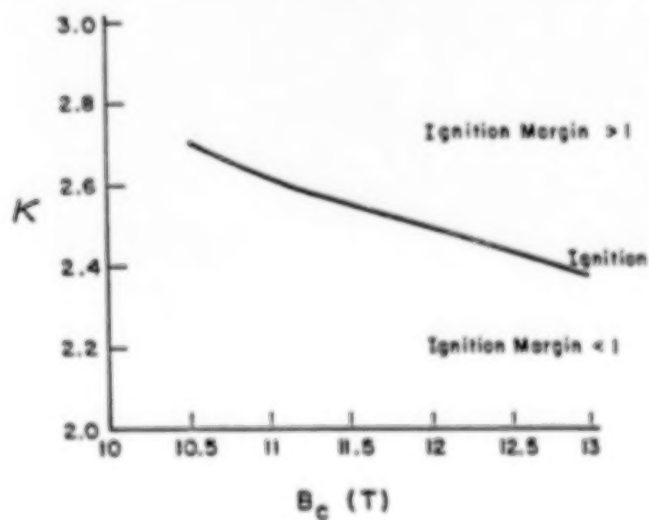
for a given  $T_i$  or  $T_e$ . The temperature of the other species is determined by a power balance on that species.

If the plasma is ignited, then  $M > 1$  and  $P_{\text{inj}} < 0$ . One has to enhance the energy loss to maintain the plasma at that temperature.

***D-<sup>3</sup>He Operation Allows Inboard Shielding  
To Be Reduced and a Magnetic Field Increase***



***Achieving D-<sup>3</sup>He Ignition Will Require  
Many Trade-Offs***



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### Power Balance Calculation Summary

- Under present NET (Next European Torus) scaling guidelines, a D-<sup>3</sup>He plasma would ignite in an early phase of a modified (~10% cost penalty) D-T ITER experiment
  - Highest-impact modifications would be to reduce shielding thickness, move the plasma to a smaller major radius, and increase the magnetic field at the coils
  - CIT could similarly achieve  $Q \geq 2$
- Under the most pessimistic of the scaling laws, neither a D-<sup>3</sup>He plasma nor a D-T plasma would ignite in ITER unless the size were increased
- The question of whether D-<sup>3</sup>He physics could be demonstrated on the next generation D-T experiments deserves careful consideration, even at modest cost increase for the device

REQUIREMENTS OF DHe-3 PHYSICS AND TECHNOLOGY VS THE DT CYCLE

AREA	HARDER	SIMILAR	EASIER
PHYSICS			
FUELING			
PLASMA HTG			
CURRENT DR			
FW HT FLUX			
MASS POWER DENSITY			
MATERIALS			
HIGH EFF. OP			
SAFETY			
ENVIRONMENT			
LICENSING			

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## Conclusions

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- D-<sup>3</sup>He fusion faces a more difficult physics development path but an easier technology development path than does D-T fusion
- Early D-<sup>3</sup>He tests in next generation (CIT and ITER) D-T fusion experiments might provide a valuable D-<sup>3</sup>He proof-of-principle at modest cost (~10%)
- At least one high-leverage alternate concept should be vigorously pursued
- Space applications of D-<sup>3</sup>He fusion are critically important to large-scale space development

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LUNAR HYDROGEN: A RESOURCE FOR FUTURE USE AT

LUNAR BASES AND SPACE ACTIVITIES\*

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\*Presented at the symposium "Lunar Bases and Space Activities in the 21st Century," Houston, TX, April 5-7, 1988.

Hydrogen abundances have been determined for grain size separates of five lunar soils and one soil breccia. More than 80 percent of the hydrogen in lunar soils is found in the sub-45 micron grain size fraction. Abundances of hydrogen in bulk lunar soils and soils from the Apollo 17 deep drill core are directly correlated to the  $I_S/FeO$  maturity parameter. The average  $^1H/^4He$  atom ratio for soils from the deep drill core was 8.5.

With a commitment to the Space Station and the increasing interest in a potential Lunar Base, there is a need to find an extraterrestrial source of hydrogen for consumables and propellants which might be available at a reduced cost. In order to know if usable quantities of hydrogen are present in the near-earth region of space (i.e. on the moon) a study of hydrogen abundances and distributions in lunar materials has been undertaken. An understanding of the potential sources of hydrogen on the lunar surface must be obtained. If such sources of hydrogen can be identified, future space activities will be enhanced by having another source of consumables and propellants available for use. The extreme costs of transporting hydrogen from earth would be reduced if sufficient quantities of hydrogen were available in the near-earth region of space.

Hydrogen is the most abundant element in the cosmos. The sun is constantly burning hydrogen and hydrogen is being lost from the sun. In addition, hydrogen is streaming away from the sun in the form of the solar wind. Hydrogen is the most abundant element in the solar wind. It is known that the lunar surface has been irradiated by the solar wind. From the detailed studies of lunar materials, it has been shown that selected volatile elements present in the solar wind (i.e. H, He, C, N, Ne, Ar, etc.) are enriched on the surfaces of exposed materials. The longer the surfaces of the samples are exposed to the solar wind the greater the amounts of solar wind species trapped in the lunar materials.

In order to understand the hydrogen abundances and distributions in lunar materials we have been making hydrogen measurements in a wide variety of soils, grain size separates, breccias, igneous rocks along with samples from the deep drill cores. A microanalysis technique utilizing helium ionization equipped gas chromatography was employed for measuring hydrogen released by pyrolysis from milligram quantities of soils (Carr et al., 1988). Our studies have shown that essentially 100 percent recovery of the implanted solar wind hydrogen can be obtained by heating the soil samples at 900 °C.

Hydrogen abundances measured (Table 1) in five bulk soils range from 26 to 54  $\mu gH/g$  (within the previously reported by DesMarais et al., 1974), the lowest abundance found being that of the submature soil 71501. The hydrogen abundances calculated from the mass fractions are in excellent agreement with those found experimentally for the bulk samples. For the five soils studied in detail, over 80 percent of the hydrogen is found in the sub-45 micron size fraction. Apollo 15 soil breccia 15086 was disaggregated by freeze-thaw and ultrasonic into its different size fractions. Mass balance calculations for the hydrogen content of the breccia were in good agreement with the experimentally determined value for the bulk sample (58 and 60  $\mu gH/g$  respectively). In the case of the soil breccia 95 percent of the hydrogen is in the sub-45 micron fraction. A comparison of the  $I_S/FeO$  (a maturity indicator) and hydrogen abundance value

for 15086 with lunar soils shows that the soil breccia lies off the expected trend. The soil breccia has been enriched in its hydrogen contents as compared to lunar soils of similar maturity.

In order to show that lunar hydrogen abundances are related to soil maturity and exposure histories and not a function of depth within the lunar surface, we have analyzed soil samples from the Apollo 17 deep drill core (70002-70009) (Gibson et al., 1988). The core was taken about 400 meters southeast of Camelot Crater and was the deepest soil column (295 cm) returned from the moon. The  $I_5/FeO$  profile for the entire core shows a wide range of soil maturities. The correlation between hydrogen abundance determined in this study and soil maturity as measured by the  $I_5/FeO$  index is striking (Figure 1). One of the distinctive features of the core is the immature zone between 20 and 60 cm. As expected, we found very low hydrogen concentrations in this zone. Proceeding down the core, soils became more mature, and larger hydrogen abundances were found. Both of these results are expected from the grain size distributions in the core (Langevin and Nagle, 1980). The section of the core where hydrogen is depleted (bottom of 70009 through 70008) consisted of coarse-grained basaltic material. Gas concentrations are usually lower in larger grain sizes. The largest hydrogen abundances were found in the middle of 70006 down to the middle of 70005. These enrichments are associated with the finer-grained materials which have had a longer surface exposure.

It is important to know the H/He ratio in lunar materials in order to understand the solar abundances along with obtaining information about the potential abundances of helium if use of the  $^3He$  is ever to be utilized in fusion processes associated with space activities. Stoener et al. (1974) measured hydrogen and helium abundances on nine samples from the Apollo 17 deep drill core. They found unusually high H/He ratios for the samples. It is believed that the hydrogen abundances reported by them represent a component of terrestrial water contamination. Using our hydrogen abundances and the helium values of Stonner et al., the average  $^1H/^4He$  ratio for the Apollo 17 deep drill core was found to be 8.5. This is in the expected range of 7 to 10 for the solar wind  $^1H/^4He$  atom ratio.

Our hydrogen abundance studies have provided important baseline information for engineering models undergoing study at the present time. From our studies it appears that there is sufficient hydrogen present in selected lunar materials which could be recovered to support future space activities. It is well known that hydrogen can be extracted from lunar soils by heating between 400° and 800 °C. Recovery of hydrogen from regolith materials would involve heating with solar mirrors and collecting the released hydrogen. In order to have an understanding of the magnitude or size of the hydrogen recovery process required to recover sufficient hydrogen for space operations, we are reminded that the Space Shuttle requires around 102,000 kg hydrogen for lift-off from its launch pad on earth. Extraction of hydrogen from a mature lunar soil typical of some of those present at the Apollo 11 or 17 sites would require processing a quantity of soil equal to that found from an area the size of 28 football fields mined to a depth of 10 feet. In comparison to mining operations found on the earth, such mining operations are considered quite small.

Current baseline models for the lunar base are requiring the production of 1000 metric tons of oxygen per year. From this requirement it follows that around 117 metric tons per year of hydrogen would be required for the produc-

tion of water. Gerisch (1988) has recently examined the equipment requirements for a lunar strip mining system. To support the recovery of 117 metric tons of hydrogen per year, it has been shown that the three drum slusher type of mining equipment could meet the production requirements. The delivery weights of such equipment to the lunar surface would be around 30,000 kilograms. These weights are compatible with shuttle payload capabilities. Gerisch (1988) noted that the three drum cable-way scraper-bucket or slusher mining system could be a viable system for lunar mining operations. Such a system could mine the regolith materials required for hydrogen production on the lunar surface. The ability to obtain hydrogen from the lunar regolith would assist in lowering the operating costs of any lunar base.

#### References

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- Gerisch, R.E. (1988) in Space Resources, NASA-ASEE Summer Study held at the California Space Institute, 1984. (in preparation).
- Gibson, E.K. Jr., et al. (1988) *Lunar and Planet. Sci. XIX*, 387-388.
- Langevin, Y. and Nagle, J.S. (1980) *Proc. 11th Lunar and Planet. Sci. Conf.*, 1415-1434.
- Stoenner, R.W. et al. (1974) *Proc. 5th Lunar Sci. Conf.* 2211-2229.



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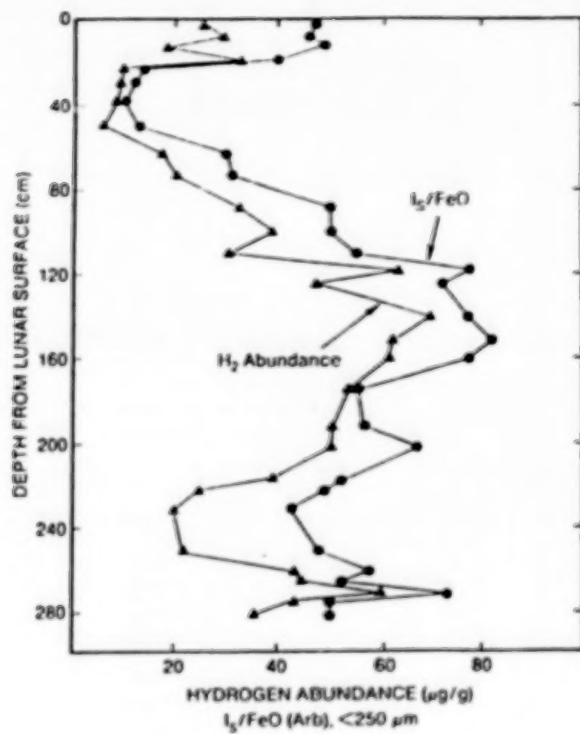
TABLE 1  
Hydrogen Abundances of Lunar Soil Size Fractions and  
Mass Balance Calculations

	10084, 149			12070, 177			15021, 7		
Size Fraction (um)	Hydrogen Content (ug/g)	Weight %	Hydrogen Calculated in Bulk Soil (ug/g)	Hydrogen Content (ug/g)	Weight %	Hydrogen Calculated in Bulk Soil (ug/g)	Hydrogen Content (ug/g)	Weight %	Hydrogen Calculated in Bulk Soil (ug/g)
20	146.7	25.78	37.8	107.4	22.35	24.0	128.5	23.87	29.4
20-45	29.7	18.33	7.3	30.1	17.34	5.2	51.1	22.96	11.7
45-75	24.4	15.01	3.7	16.2	14.82	2.4	22.4	15.61	3.5
75-90	20.1	5.01	1.0	9.0	5.09	0.5	20.8	4.37	1.1
90-150	20.2	12.24	2.5	8.7	13.37	1.7	15.5	13.26	2.1
150-250	11.3	9.06	1.0	7.5	10.60	0.8	6.4	9.25	0.8
250-500	15.7	8.73	1.4	9.4	8.80	0.8	6.7	7.23	0.6
500-1000	7.2	5.82	0.4	8.5	7.63	0.6	11.8	3.31	0.4
Total Hydrogen Calculated in Bulk (ug/g)		55.1			35.5			49.8	
Total Hydrogen Found Experimentally in Bulk (ug/g)		54.2			39.2			49.6	

	60501, 1			71501, 138			15086, 202 Breccia			
Size Fraction (um)	Hydrogen Content (ug/g)	Weight %	Hydrogen Calculated in Bulk Soil (ug/g)	Hydrogen Content (ug/g)	Weight %	Hydrogen Calculated in Bulk Soil (ug/g)	Size Fraction (um)	Hydrogen Content (ug/g)	Weight %	Hydrogen Calculated in Bulk Soil (ug/g)
20	124.1	24.17	29.9	126.4	17.67	22.3	20	126.3	28.62	50.5
20-45	43.8	17.76	7.6	47.2	17.67	8.3	20-45	11.9	19.05	4.2
45-75	16.1	13.48	2.2	18.5	15.60	2.9	45-90	11.7	14.30	2.1
75-90	12.8	4.40	0.4	9.4	4.42	0.5	90-150	4.8	12.55	0.5
90-150	9.6	11.54	1.1	7.7	14.75	1.1	150-250	2.3	9.12	0.2
150-250	5.2	9.72	0.5	2.1	11.51	0.2	250-500	2.7	7.51	0.2
250-500	4.4	10.75	0.5	2.4	10.69	0.3	500-1000	1.9	4.85	0.1
500-1000	2.4	8.22	0.2	1.7	6.64	0.1				
Total Hydrogen Calculated in Bulk (ug/g)		42.6			35.7		Total Hydrogen Calculated in Bulk (ug/g)			57.8
Total Hydrogen Found Experimentally in Bulk (ug/g)		35.8			25.7		Total Hydrogen Found Experimentally in Bulk (ug/g)			60.4



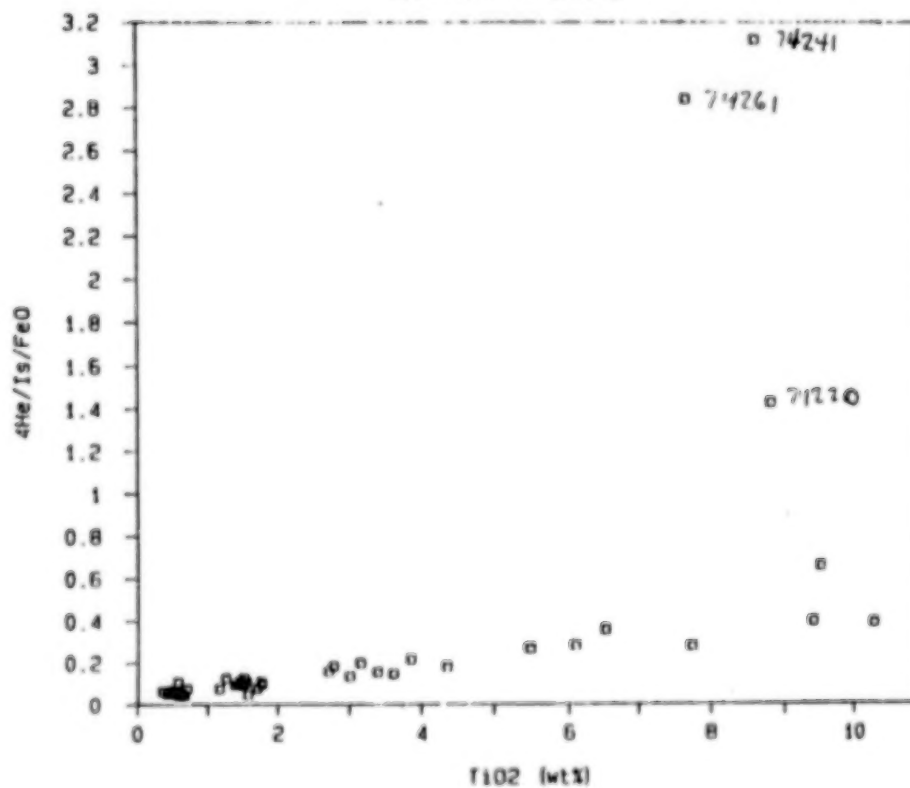
# APOLLO17 DEEP DRILL CORE

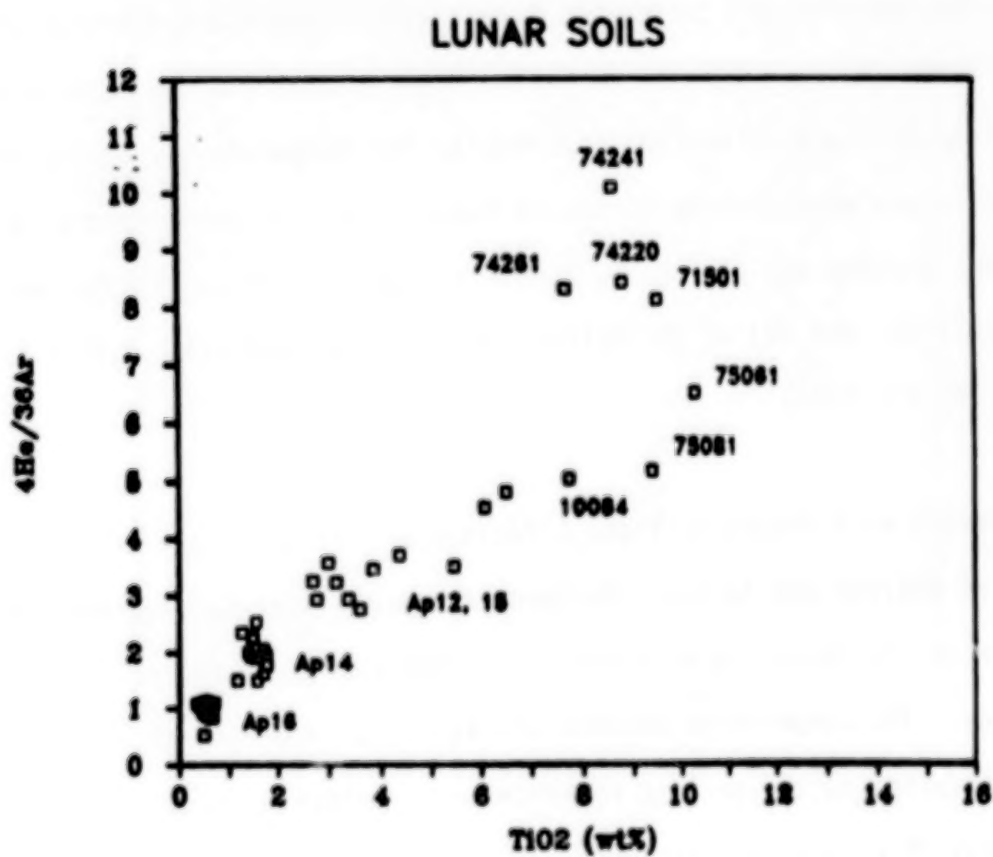
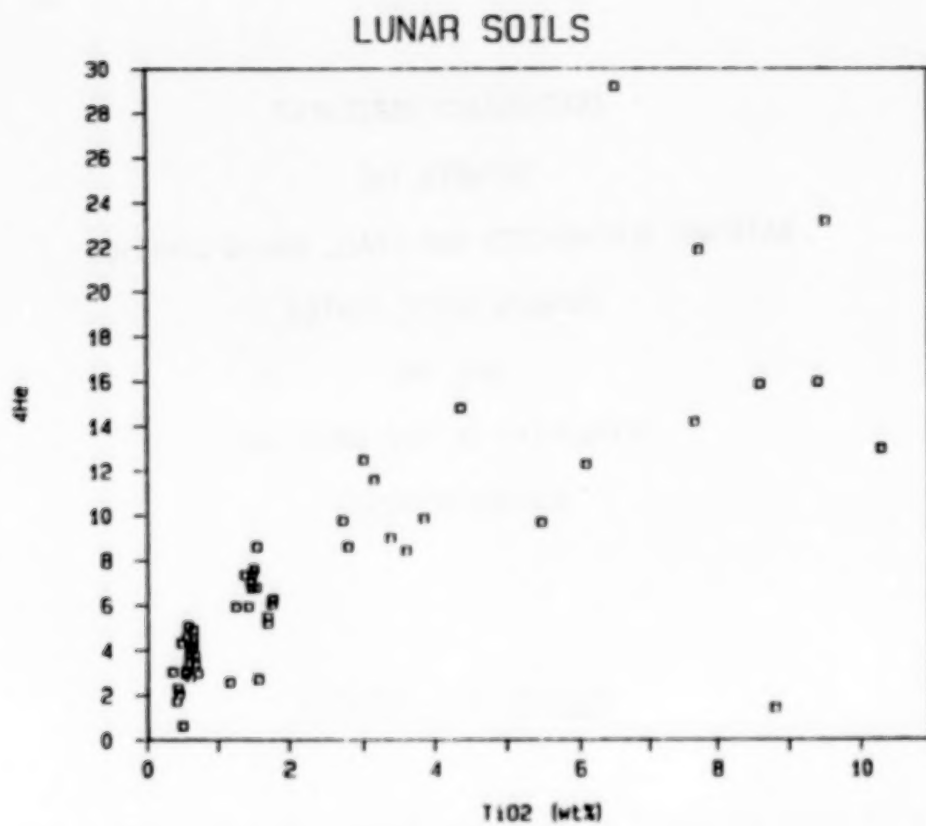


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Figure 1. Hydrogen Abundances and I<sub>2</sub>/FeO Values for Apollo 17 Deep Drill Core.

## LUNAR SOILS





INTERAGENCY AGREEMENT  
BETWEEN THE  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
JOHNSON SPACE CENTER  
AND THE  
DEPARTMENT OF THE INTERIOR  
BUREAU OF MINES

ARTICLE I -- PURPOSE

The purpose of this Agreement between the Bureau of Mines (BOM) of the Department of the Interior and the National Aeronautics and Space Administration, Johnson Space Center (JSC), is to define the research and development areas of mutual interest, and to provide opportunity for cooperative programs in space exploration and establishing permanent lunar bases, as authorized by Section 601 of the Economy Act of June 30, 1983, as amended (31 USC §1535), and Section 203(C) (5) and (6) of the National Aeronautics and Space Act of 1985, as amended (42 USC §2473).

The Agreement will insure full and effective use of the capabilities and expertise of DOI/BOM and NASA/JSC to identify, plan, execute, and monitor space program elements involving rock mechanics, mining, and resource extraction technology. The cooperation between the agencies is agreed to extend from mutual consultation to specific research and development tasks in the indicated areas of science and technology.

## ARTICLE II -- PROGRAM COORDINATION

DOI/BOM and NASA/JSC shall implement a regularly scheduled exchange of planning and development of information related to areas of DOI/BOM involvement in space exploration and utilization. These exchanges can be in terms of written or verbal communications, mutual visits, or through joint committee meetings. Each agency will designate a key person to act as a liaison for this inter-agency cooperative effort.

## ARTICLE III --NASA/JSC CONTRIBUTION

- A. NASA/JSC will provide the necessary information on the past accomplishments, current activities, and future plans on the lunar base and planetary exploration programs as related to DOI/BOM involvement. NASA/JSC will also provide, as necessary, lunar and planetary samples and environmental data for further DOI/BOM and NASA/JSC cooperative investigations. In addition, NASA/JSC will also provide data on lunar and planetary samples for further property and fragmentation studies.
- B. Extraterrestrial samples of NASA/JSC are not committed by this Agreement. Normal NASA/JSC procedures will be followed for access to samples including technical reviews of proposed work and specific security plans for safeguarding samples. NASA/JSC will collaborate with DOI/BOM to identify best samples for specific studies.

#### ARTICLE IV -- DOI/BOM CONTRIBUTION

Based on the input from NASA/JSC, DOI/BOM will provide technical support for both inhouse and contract research and development related to rock and regolith sampling, mining, mineral extraction, and property determination. Based on input from NASA/JSC, DOI/BOM, will provide technical support for research and development activities related to rock and regolith sampling and property determination, mining, mineral extraction and processing. This will cover areas vital for establishing manned lunar or planetary bases. The support will consist of consultation in areas of DOI/BOM expertise and of some testing to characterize the extraterrestrial material samples. DOI/BOM will also participate in the design and development of equipment or methods to be used in lunar or planetary environment for either sample collection or excavation including rock fragmentation, and mineral extraction and processing.

#### ARTICLE V -- FUNDING

- A. Nothing in this Agreement shall be construed to imply any commitment of NASA/JSC's or DOI/BOM's funds or appropriations to each other. In addition, each party's resource commitment to this Agreement is subject to availability of appropriated funds.
- B. For special requested projects or tasks involving the commitment of funds, the initiating party will process the appropriate procurement and funding document.

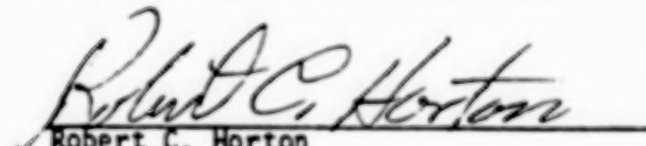
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ARTICLE VI -- DURATION, MODIFICATION, AND TERMINATION

This Agreement shall become effective upon the last signature hereto, and will remain in effect for 3 years, or until such time as it is terminated upon 90 days' written notice of either party. However, upon mutual written agreement, said Agreement may be terminated at any time.

FOR: DEPARTMENT OF THE INTERIOR

  
Robert C. Horton  
Director  
Bureau of Mines

Date Nov. 4, 1955

FOR: NATIONAL AERONAUTICS AND  
SPACE ADMINISTRATION

  
Robert C. Goetz  
Acting Director  
Lyndon B. Johnson Space Center

Date FEB. 3, 1956



## United States Department of the Interior

BUREAU OF MINES  
2401 E STREET, NW.  
WASHINGTON, D.C. 20241

June 20, 1986

Mr. Jesse W. Moore  
Director  
Lyndon B. Johnson Space Center  
Houston, Texas 77058

Dear Mr. Moore:

The research staffs of our organizations have established mutual research interests resulting in the signing of Interagency Agreement No. 14-09-007-1228. We, in the general area of space exploration and utilization, consider this as an extension of our previous cooperative research in the Apollo program. At that time, working with James J. Gangler from NASA Headquarters, the Bureau participated in the basic research on lunar resource utilization as a member of the Working Group on Extraterrestrial Resources. As early as 1962, this group was developing techniques for reducing the dependence of lunar and planetary exploration on terrestrial supplies. I am pleased to see that cooperation is being reestablished and see great potential for benefits for both our agencies.

The ratified Agreement requires that each agency designate a key person to act as liaison for this interagency cooperative effort. The liaison functions in the Bureau of Mines will be under the direction of the Deputy Director, David S. Brown.

The technical management aspects will be handled by the Assistant Director--Mining Research, Dr. David R. Forshey, and his staff in Washington, D.C. The lead Center for this research will be the Twin Cities Research Center (TCRC), Minneapolis, Minnesota, under the direction of the Research Director, Dr. Lewis V. Wade. The cooperative effort was initiated by Egons R. Podnieks, Senior Staff Scientist at TCRC, and he will continue to provide the coordination and liaison within the scope of the Agreement.

Sincerely,

David S. Brown

Director

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## **$^3\text{He}$ on the Moon**

### **Issues:**

1. What is the range of measured  $^3\text{He}$  concentrations?
2. How does  $^3\text{He}$  abundance vary from place to place on the moon?
3. Why is  $^3\text{He}$  correlated with titanium?
4. How does  $^3\text{He}$  vary with depth in the lunar regolith and what is the depth of the lunar regolith containing significant  $^3\text{He}$ ?
5. How can we predict  $^3\text{He}$  abundances in a lunar region without having samples?
6. Is it possible that regions of ancient regolith have higher  $^3\text{He}$  concentrations?
7. Is it possible that some lunar process have concentrated  $^3\text{He}$  in some regions or "ore bodies"?
8. Is it practical to mine enough  $^3\text{He}$  to provide a significant product?
9. What are the power requirements of the mining system?
10. What is the weight of the mining system?
11. Should the mined material be sized before extraction?
12. Should the mined material be mineral concentrated or beneficiated?
13. What is the best way to liberate the  $^3\text{He}$ ?
14. What is the best way to collect and store the  $^3\text{He}$ ?
15. What is the power requirements of the system which extracts the  $^3\text{He}$ ?
16. How much does this system weigh?
17. What are the economics of the overall scheme?
18. What are the political and legal ramifications?

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PROCESSES AND ENERGY COSTS FOR MINING LUNAR HELIUM-3

I.N. Sviatoslavsky

Fusion Technology Institute  
and

Wisconsin Center for Space Automation and Robotics  
University of Wisconsin - Madison  
Madison, WI 53706

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## **SUBJECTS COVERED:**

### **1) Mining and Extraction Processes:**

•Excavating	]	<b>Lunar Regolith</b>
•Conveying		
•Beneficiating		
•Heating		
•Energy Recovery		
•Redeposition	]	<b>Solar Wind Products</b>
•Collecting		
•Condensing		
•Transporting		

### **2) Masses of Equipment Required**

### **3) Process Power Requirements**

### **4) Energy Payback**

### Solar Wind Gas Release Predicted for Maria Regolith When Heated to 700°C

	He3	He4	H <sub>2</sub>	Carbon	N <sub>2</sub>
Concentration in Maria regolith (ppm or g/tonne mined)	9x10 <sup>-3</sup>	30	50-60	142-226	102-153
Concentration in Grains < 50 μ (g/tonne mined)	8.1x10 <sup>-3</sup>	27	50	166	115
Amount Released at 700°C (g/tonne mined)	7x10 <sup>-3</sup>	22	43 (H <sub>2</sub> ) 23 (H <sub>2</sub> O)	13.5 (CO) 12 (CO <sub>2</sub> ) 11 (CH <sub>4</sub> )	4
Mass Obtained per kg of He3 (tonnes)	10 <sup>-3</sup>	3.1	6.1 (H <sub>2</sub> ) 3.3 (H <sub>2</sub> O)	1.9 (CO) 1.7 (CO <sub>2</sub> ) 1.6 (CH <sub>4</sub> )	0.5

### Prime Considerations in the Design of Lunar Miner Mark-II

•Efficient utilization of lunar regolith as a source of He-3 implies deep mining, down to 3 meters.

•Disposition of rejected and processed regolith during and after mining to minimize impact on the lunar landscape.

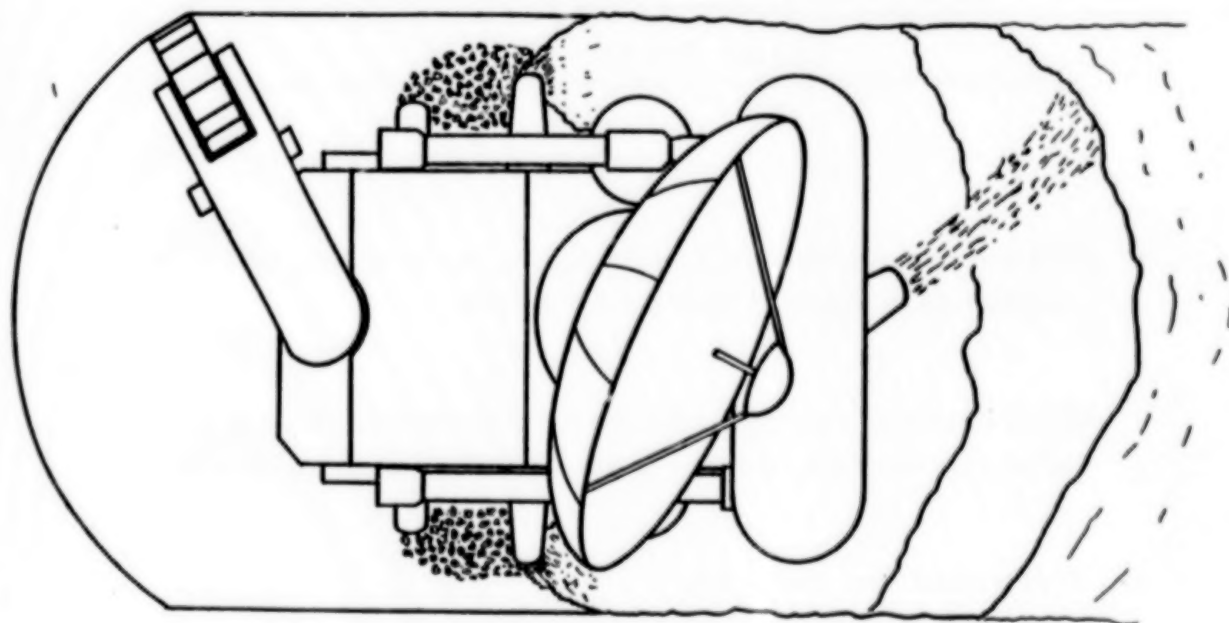
Convenient gas handling.

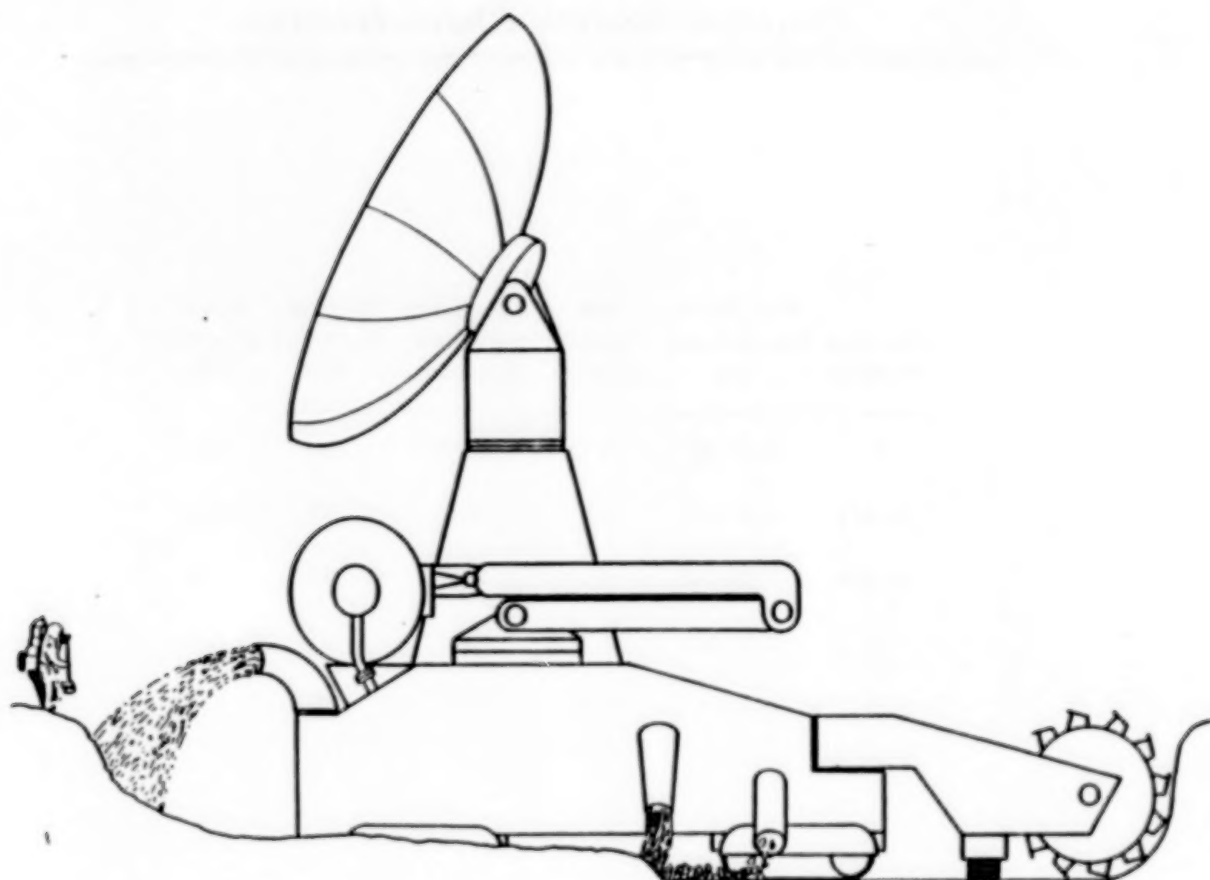
## ***Lunar Miner Mark-II***

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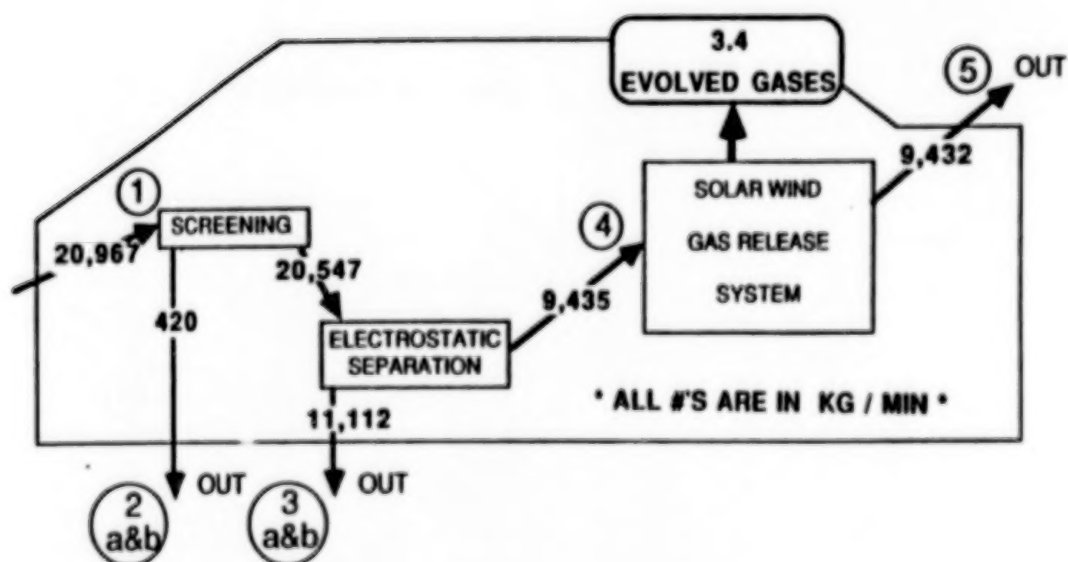
- Use of a bucket wheel excavator for excavating a deep wide trench.
- Deposit rejected regolith along the sides of the miner and eject the processed regolith from the back to refill trench uniformly.
- Service vehicles place empty gas cylinders along one side of intended mining route.  
Miner picks up cylinders one at a time and deposits full ones on the other side of trench.  
Service vehicles pick up full cylinders and transport them to condensing station.

### **TOP VIEW OF LUNAR MINER MARK-II**





**SIDE VIEW OF LUNAR MINER MARK-II**



NOTE: NO.'s IN CIRCLES REPRESENT INTERNAL REGOLITH CONVEYOR NO.

**FIGURE C. REGOLITH MASS FLOW RATES (kg/min)**

## Conveyor System Characteristics

Conveyor Number	Vert./Horiz. Displacement (m)	Belt Speed (m/min)	Mass Transport Rate (kg/min)	Mass of Conveyor (kg)	Power Required (kW)
1	0.5/1.25	15.4	20970	120	2.35
2a & b	-0.25/2.0	0.2	210	418	0.03
3a & b	-0.25/2.0	4.1	5767	418	0.68
4	2.25/3.5	6.9	9437	479	1.4
5	0.5/1.5	6.9	9437	187	0.76

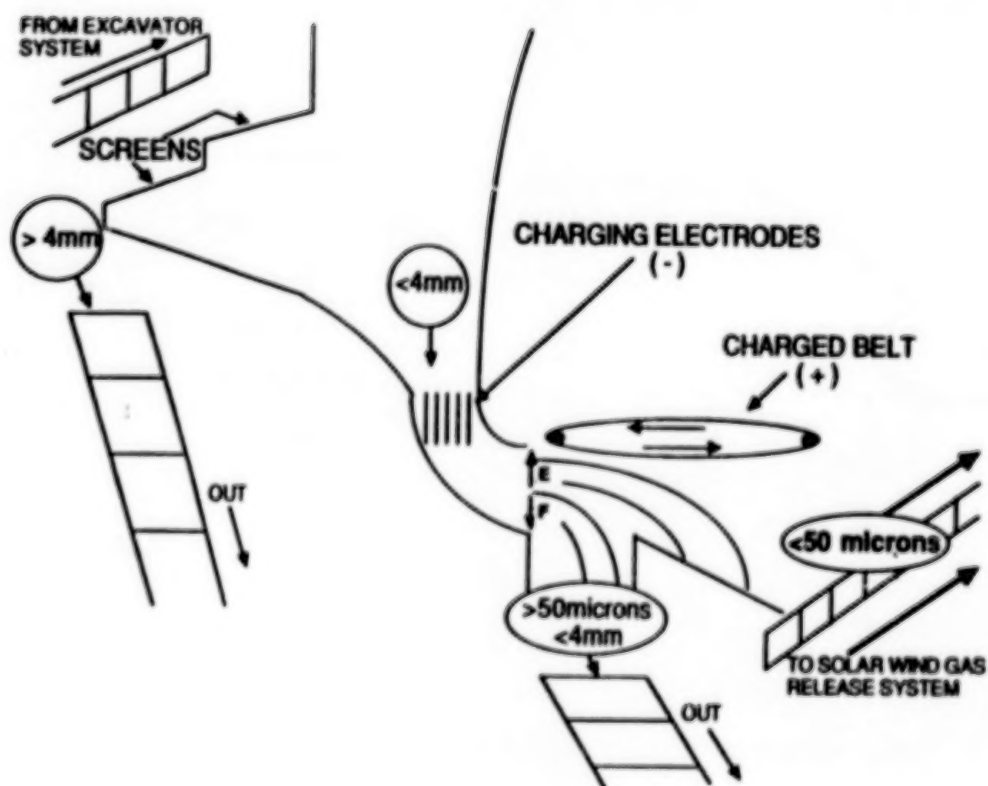


FIGURE B. INTERNAL REGOLITH BENEFICIATION SYSTEM



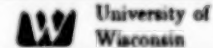
## *Heater Design*

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- Regolith processing rate is limited by energy supply, making heat recovery mandatory
- The heater is designed with a preheater, supplemental heater and a recuperator, achieving 85% energy recovery

## *Heating of Regolith*

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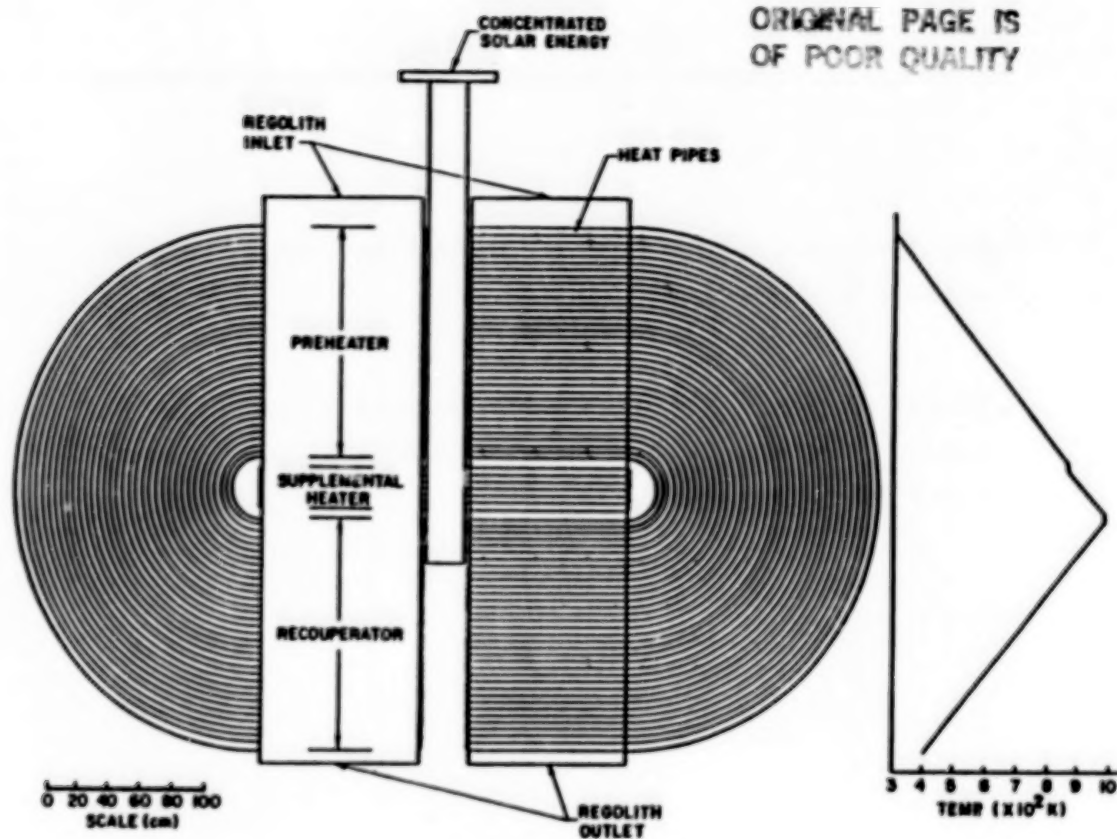


### ASSUMPTIONS

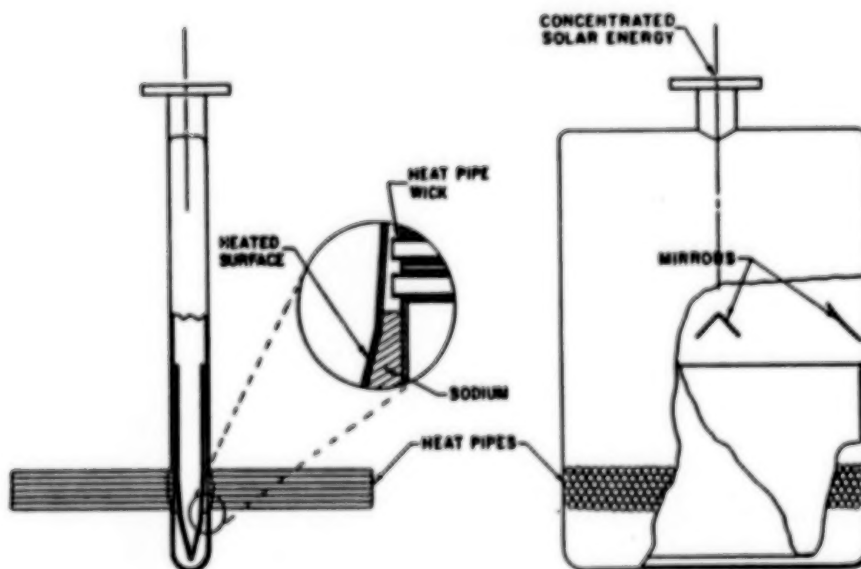
- Solar energy beamed from 110 m diameter solar collector to a 10 m diameter dish mounted on miner
- Oven enclosure will have 0.1 - 0.2 atm of solar wind products

Deissler Boegli method used to determine effective thermal conductivity of regolith

- Dietus Boelter formulation used to obtain heat transfer coefficients: these were benchmarked against UW experiments performed in 1980-82 with remarkable agreement



**VIEW OF REGOLITH HEATER AND A REGOLITH  
TEMPERATURE PROFILE 'S A FUNCTION OF HEIGHT**



**TWO VIEWS OF SUPPLEMENTAL HEATER**

### ***Gas Collection System Compressor***

---

<b>Compressor Type</b>	<b>Reciprocating</b>
<b>Inlet Pressure (MPa)</b>	<b>0.02</b>
<b>Outlet Pressure (MPa)</b>	<b>15</b>
<b>Number of Stages</b>	<b>6</b>
<b>Power Requirement (kW)</b>	<b>160</b>
<b>Estimated Mass (tonnes)</b>	<b>1.2</b>

---

### ***Selected Mobile Miner Parameters***

---

<b>Annual collection rate of He3 (kg)</b>	<b>33</b>
<b>Mining hours/year</b>	<b>3942</b>
<b>Excavation rate (tonnes/hour)</b>	<b>1258</b>
<b>Depth of excavation (m)</b>	<b>3</b>
<b>Width of excavated trench (m)</b>	<b>11</b>
<b>Forward speed of miner (m/h)</b>	<b>23</b>
<b>Area excavated per year (km<sup>2</sup>/y)</b>	<b>1.0</b>
<b>Processing rate (tonnes/hour)</b>	<b>556</b>
<b>Process energy requirement (MW)</b>	<b>12.3</b>

### ***Selected Mobile Miner Parameters (contd.)***

---

Heat recovery (%)	85
Number of conveyors required	5
Assumed inlet regolith temperature (K)	300
Maximum regolith temperature in heater (K)	973
Temperature of regolith deposited back (K)	400
Pressure in heater enclosure (MPa)	.02
Pressure of gases in cylinders (MPa)	15
Estimated operating power requirements (kW)	200
Estimated total earth mass of miner (tonnes)	18

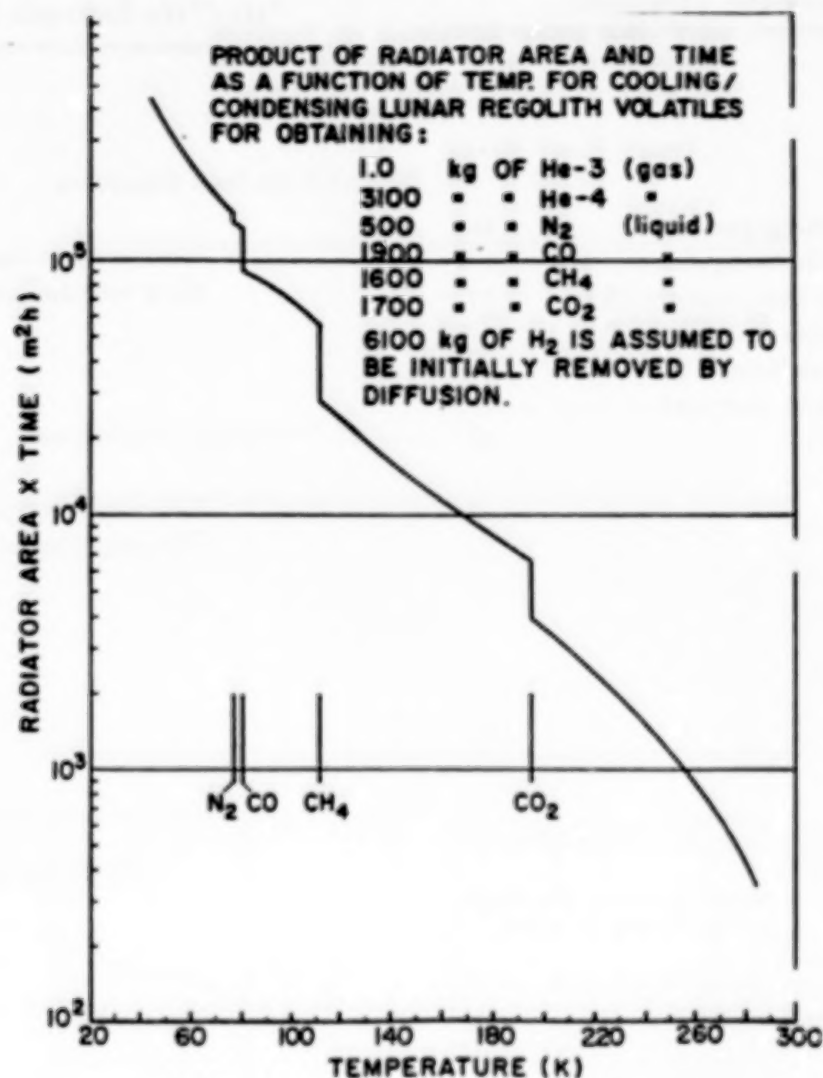
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### ***Requirements of Radiator Area and Time for Cooling/Condensing Lunar Volatiles***

---

#### **Assumptions Made:**

- $H_2$  gas removed prior to cooling by diffusion through a membrane within the gas cylinders
- Each species is drained out as it condenses
- Helium species are cooled to 55 K
- Radiator mass not included in cooling calculations
- Cooling takes place during lunar night



### Radiator Area

•A radiator area of  $\sim 830 \text{ m}^2$  (29 m x 29 m) is needed to cool/condense solar wind volatiles (without H<sub>2</sub>) to obtain a kg of He-3 per lunar month.

•The area needed is  $6.9 \times 10^5 \text{ m}^2$  (833 m x 833 m) to supply 10 tonnes of He-3 per year.



## Cryogenerator Parameters

Inlet He Gas Temperature (K)	55
Outlet Liquid He Temperature (K)	1.5
Heat Rejection Temperature (K)	77
Percent of Carnot Efficiency (%)	17
Estimated Room Temp. Power (kW)	180
Liquid He Output (tonnes)	3.3
Availability (%)	50

## $^3\text{He}/^4\text{He}$ Isotopic Separation

### 1) Superleak Separator

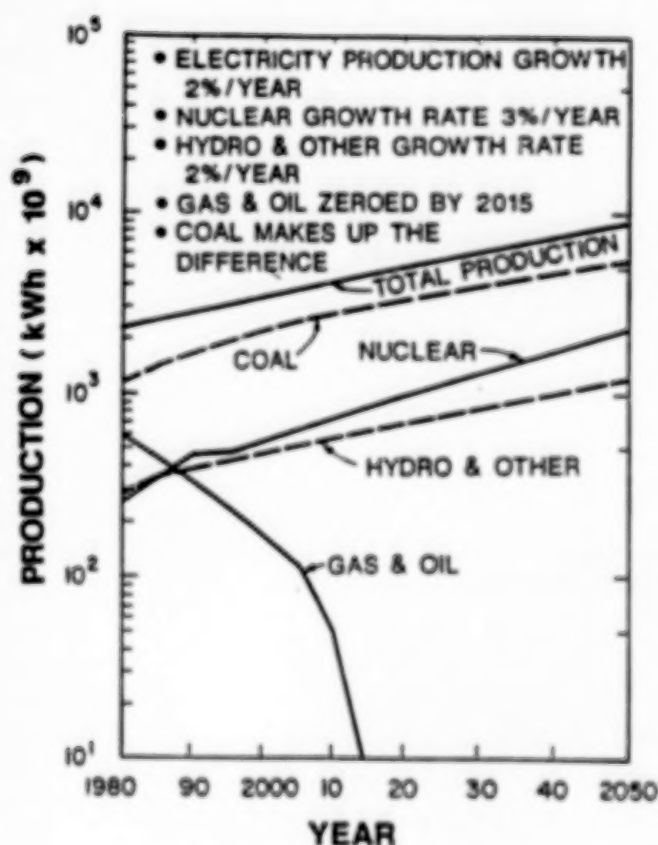
Temperature range: 1.5 K to 2.2 K

$^3\text{He}$  enrichment:  $4 \times 10^{-4}$  to  $\sim 10^{-2}$

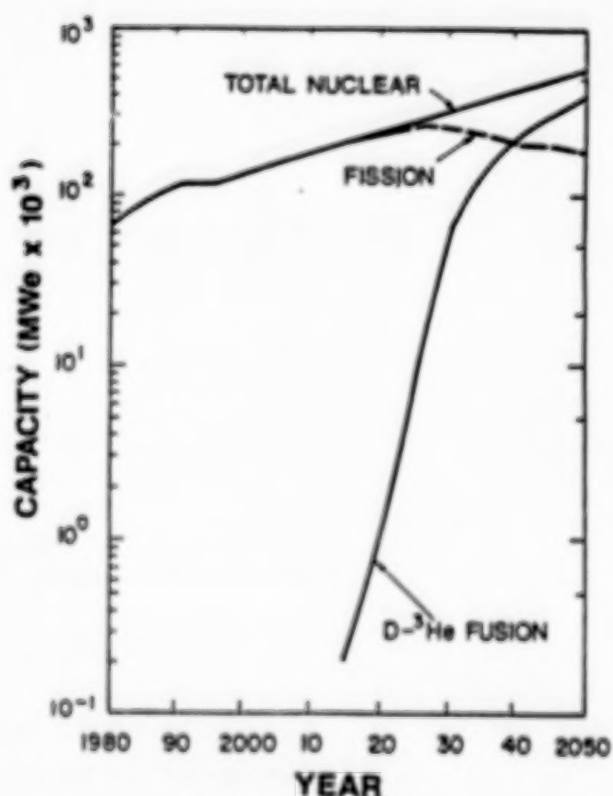
### 2) Cryogenic Distillation

Temperature range: 2.3 K to 4.2 K

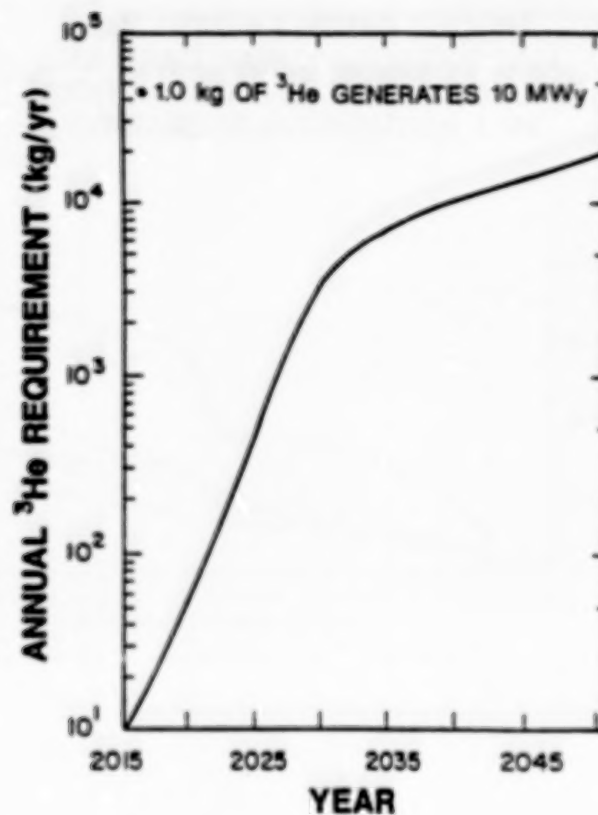
$^3\text{He}$  enrichment:  $10^{-2}$  to 0.99+



PREDICTED U.S. ENERGY DEMAND GROWTH RATE  
(Low Growth Rate Scenario)

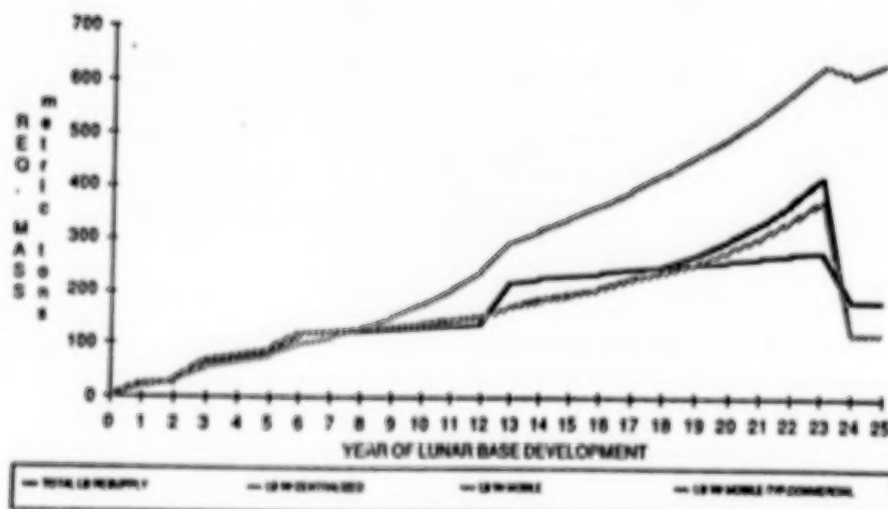


NUCLEAR CAPACITY SPLIT BETWEEN FISSION AND DHe-3  
FUSION ASSUMING A 3% TOTAL NUCLEAR GROWTH RATE

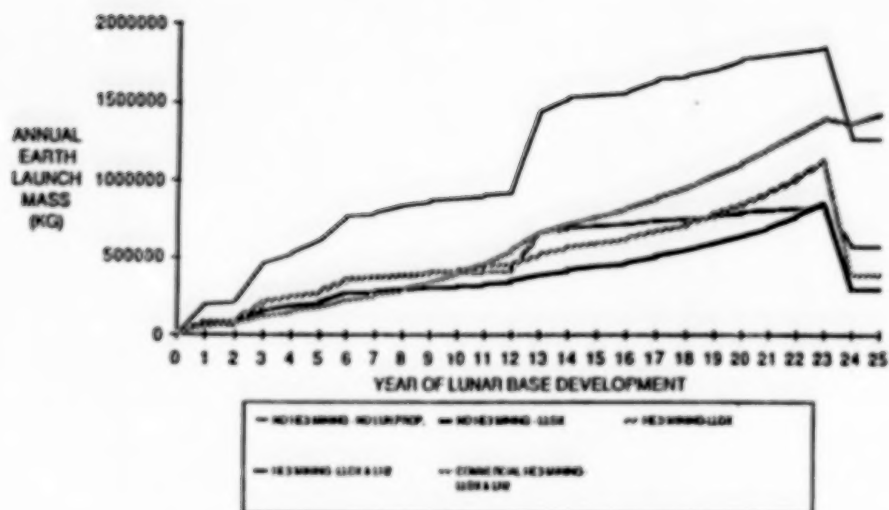


He-3 DEMAND CURVE

ANNUAL MASS DELIVERY REQUIRED  
AT THE LUNAR SURFACE FOR  
EVOLUTIONARY AND COMMERCIAL  
HE3 ACQUISITION SCENARIOS



# ANNUAL EARTH LAUNCH MASS FOR BASELINE LUNAR BASE AND EVOLUTIONARY AND COMMERCIAL HE3 ACQUISITION SCENARIOS



## Additional Resources Available from He3 Acquisition for Lunar Base Support

Resource	Application to Lunar Base	Estimated Requirement for 15-20 Person Base* (kg/y)	kg/miner-y
H <sub>2</sub> O	Life Support Consumable	4280	10.0x10 <sup>4</sup>
O <sub>2</sub>	Life Support Consumable	570	7.7x10 <sup>4</sup> (a)
N <sub>2</sub>	Life Support Consumable	323	1.7x10 <sup>4</sup>
H <sub>2</sub>	Lunar Resource Process Consumable	558	20.1x10 <sup>4</sup>

(a) O<sub>2</sub> obtained from additional processing of CO<sub>2</sub> and CO.

\*Lunar base includes full scale mining operations, science facilities, semi-closed life support system, and MMW nuclear power source.

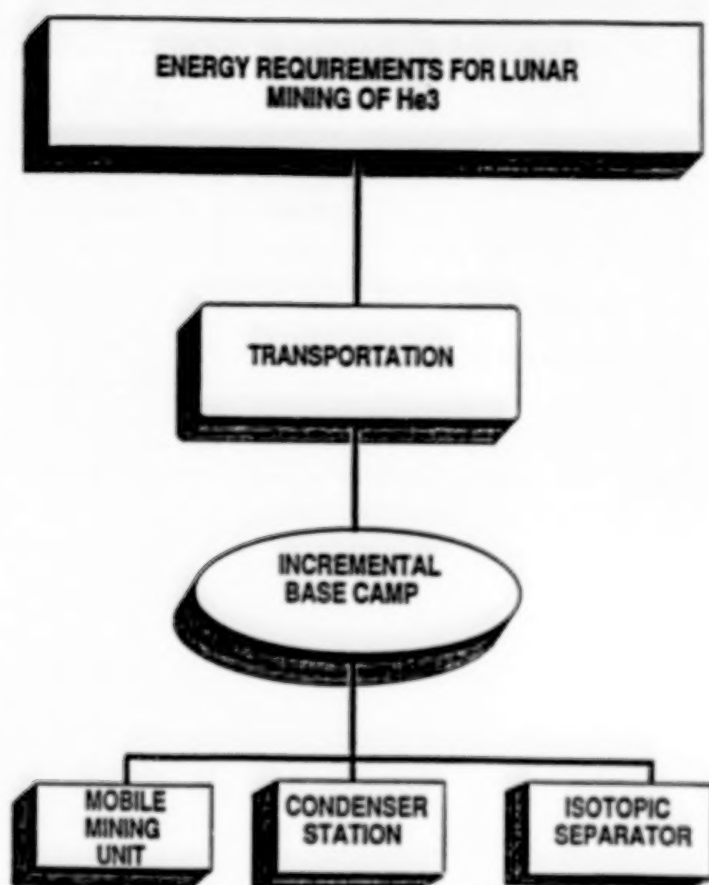


Figure 5

### Operational Energy Requirements of Lunar Mobile Miner

Operation	Source	GJ/kg He-3
Locomotion & Excavation	Battery/ Solar	13
Conveyors & Beneficiation	Battery	4
Process Heat	Solar	4100 (free)
Compressor	Fuel Cell	67
TOTAL		84

**OPERATIONAL ENERGY REQUIREMENTS  
FOR SEPARATING GASEOUS COMPONENTS FROM He3**

OPERATION	SOURCE	GJ/kg HELIUM-3
H2 SEPARATOR	PERMEABLE MEMBRANE	VERY SMALL
ROBOTIC MANIPULATOR	BATTERY	1.8
GAS CIRCULATOR	BATTERY	0.5
LQUIFIER (55 K TO 1.5 K)	PHOTOVOLTAIC	184
	<b>TOTAL</b>	<b>186</b>

**TOTAL ENERGY REQUIRED TO BRING MINING EQUIPMENT  
AND HUMANS TO THE MOON**

EQUIPMENT	EARTH MASS-kg PER kg He3 @	ENERGY TO BRING MASS TO MOON-GJ@@
MOBILE MINER	27	810
SERVICE VEHICLE	0.8	24
SOLAR MIRROR	12.4	372
RADIATOR/CONDEN.	9.0	270
He LIQ. & SEPARATOR	4	120
BASE CAMP EQUIP. (INCREMENTAL)	12.9	387
<b>TOTAL</b>	<b>66.1</b>	<b>1983</b>

① 100% SIZE OVER PRODUCTION OF 1 TONNE OF He3/YEAR FOR 20 YEARS  
② 2 GJ/kg TO TRANSPORT FROM EARTH TO MOON (INCL ROCKET  
AND CREW) AND RETURN WITH He3 TO EARTH

**Total Energy Invested to Obtain and  
Transport 1 kg of He-3 to Earth**

Operation	GJ
Transportation of Equipment	1983
Gas Separation	186
Mobile Miner (operations)	84
<b>TOTAL</b>	<b>2253</b>
Energy Released from 1 kg He-3	600,000



### Energy Payback Ratio for Mining Helium-3

Defined as =

$$\frac{\text{Energy Released by burning 1 kg He-3 with 0.67 kg of D}_2 \text{ on earth}}{\text{Sum of the total energy required for transportation + base camp + mining operations + gas separation + isotope separation}}$$

Payback Ratio is =

$$\frac{600,000 \text{ GJ}}{2253 \text{ GJ}} = 266$$

If we include energy used to manufacture the materials for building the fusion reactor:

Based on 1985 study by R. Bünde: "The Potential Net Energy Gain from DT Fusion Power Plants", Max Planck Institut für Plasmaphysik, Garching, Federal Republic of Germany, June 1985

$$4188 \text{ MWh}_{\text{th. equiv.}} / \text{MWe} \cdot 30 \text{ y}$$

We get:

Fusion Plant	5025 GJ/kg
He-3 fuel	2253 GJ/kg
<hr/>	
TOTAL	7278

$$\text{Total Energy Payback} = \frac{600,000}{7278} = 82$$

## *Conclusions*

---

- Preliminary investigations show that obtaining He-3 from the moon is technically feasible and economically viable.
- With the exception of beneficiation, the proposed procedures are state of the art.
- Mass of equipment needed from earth is of some concern, but resupply will eventually be ameliorated by the use of titanium from indigenous ilmenite.
- A complete energy payback from a DHe-3 fusion reactor utilizing lunar He-3 is ~80, providing ample incentive for commercial investment.
- Byproducts will be of great value to the resupply of a permanent lunar base and enhancement of space exploration.

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ECONOMIC GEOLOGY OF LUNAR HELIUM-3

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AA

## PREFACE

The end of the Apollo Program found humankind, and the United States in particular, on the verge of the establishment; of bases on the moon, research stations in earth-orbit, and the statement of a realistic goal of a permanent foothold on Mars by the end of the Century. In the motto of the last Apollo mission to the moon, this could have been "The End of the Beginning."

This opportunity was not grasped. Consequently, it falls to the current generation to re-ignite John F. Kennedy's torch for space. The emotional and economic energy for that torch could be supplied by helium-3, rare on Earth, but discovered and sampled (see reports summarized by Taylor, 1982) by the Apollo astronauts and scientists. Helium-3 and several other potentially valuable by-products of its production are slowly but continuously implanted in the lunar soils by the solar wind. The workers at the Wisconsin Fusion Technology Institute, "Astrofuel" (Wisconsin, 1988). Some of the important results of the Wisconsin analysis are summarized here.

Inherently safe and potentially low cost fusion reactors fueled by helium-3 might become the basis for producing large quantities of continuously available electrical power in space, for highly efficient space propulsion to and from Mars, and for life giving by-products that insure the self-sufficiency of settlements on the moon (Kulcinski and Schmitt, 1987). Indeed, fusion power plants fueled by helium-3 from the moon could supply the electrical energy human civilization will require to maintain and expand its quality of life as we enter the Third Millennium (Wittenberg, et al, 1986) and as we move that civilization toward the stars.

A preliminary estimate (Kulcinski and Schmitt, 1987) of the commercial price of lunar helium-3 delivered to the Earth in the first quarter of the 21st Century is about \$1 billion per metric tonne. This is roughly equivalent to \$7 per barrel oil at today's prices. Its value today is about \$2 billion per tonne if matched against the cost of fuels currently used to produce electricity. The foregoing estimates also do not take into account the value of by-products from lunar helium-3 production that will be needed in space or the value of the spin-off of Astrofuel related technologies.

The principle advantages of the helium-3 fusion power cycle over other nuclear cycles include:

1. About 99 percent of the energy released is in charged particles (protons) that are non-radioactive and that induce no radioactivity in other materials.



2. High efficiency (70-80 percent) in energy conversion due to the direct conversion of charged particles to electricity.
3. Less waste heat to be rejected due to high efficiency.
4. Energy of the few neutrons released (1 percent of total energy) is only one-fourth that released in other fusion cycles and create no significant quantities of long lived radioactive waste.
5. A potentially shorter time to licensed commercialization than for other fusion cycles due to absence of significant radioactivity and waste heat.

If our estimates of the price of delivered helium-3 for deuterium/helium-3 power plants prove correct, such power plants will provide much lower cost electricity as well as much less environmental impact than other potentially competing power sources in the 21st Century.

The only major technical disadvantage of the deuterium/helium-3 fusion cycle is that the ignition temperature required to initiate fusion is about four times higher than for the competing deuterium/tritium cycle. This disadvantage appears to be becoming less and less significant as new fusion confinement technologies are developed.

Sufficient helium-3 is available on Earth (largely from tritium decay and natural gas) for development and prototype testing of deuterium/helium-3 power plants. Therefore, the primary issues that must be addressed to determine the feasibility of a commercial helium-3 industry are, first, the technical and economic feasibility of deuterium/helium-3 commercial reactors and, second, the technical and economic feasibility of providing lunar helium-3 to fuel such reactors. This second issue can be resolved objectively through the art and science of economic geology. The outline that follows summarizes the parameters that would need to be considered in an analysis of the economic geology of lunar helium-3. (This Preface was derived from the Introduction of a paper by Schmitt, 1988.)

## INTRODUCTION

Economic geology evaluations of Lunar He-3 should answer the question: Can lunar He-3 be sold on Earth with sufficient profit margins and low enough risk to attract capital investment in the enterprise?

### Potential Value of the Resource/tonne

He-3:     \$1-2 Billion/tonne  
          Equivalent to a value of \$6-12/tonne of regolith mined  
          as compared to about \$220/tonne for calcined kaolin ore

\$3/tonne for rutile ore, and \$220/tonne for perlite filter aid ore. The profit margin within each of these values is about 30-50%.

By-Products for use in space: \$1 Billion/tonne He-3

Potential Resource Base

1,000,000 tonnes He-3

Probable Recoverable Reserves

25 tonnes He-3/km<sup>2</sup> of high Ti regolith mined to 3 m depth with 60% recovery of 30 ppm He average grade (after Cameron, 1988).

Demand

Unknown at this time, but potentially 100,s of tonnes by 2050.

Parameters to Consider in Economic Geology Evaluations

- Geology
- Exploration
- Access
- Mine Planning
- Mining
- Beneficiation
- Processing
- Support
- Finances
- Politics

GEOLOGY

General

Regional Targets

Known old (mature) high Ti maria

High proportion of agglutinates and ilmenite

Low proportion of coarse grained material

Inferred high-Ti Maria

Candidate Mine Site Considerations

Regolith Depth

Boulder Distribution

Low Grade Unit Distribution

Low Recovery Unit Distribution

Available Dump Sites

## General Regolith Geology Considerations

Composition

Fragment/size distribution

Heterogeneities

Regolith Breccia/Agglutinates

Cold Traps for He-3 that will enhance grade

## New Data Required

First basic question is: Can sites for He-3 mining be selected from existing data with sufficient confidence to attract investors?

Answer is: We don't know yet, but is it worth investing significant resources to find out?

Second basic question is: Can D/He-3 fusion development proceed without the proof of He-3 reserves on the moon that can support commercialization?

Answer is: Probably not beyond the research phase.

Precursor Missions (if existing data proves to be insufficient to attract investors)

Target best candidate sites

Evaluate based on set criteria

Pick first site that meets criteria

## ACCESS

### Logistics Support Costs

Earth to moon

People/consumables/equipment

Moon to Earth

He-3/people

Moon to space

Consumables (by-products) Launch Frequency

### Flight/Delivery Risk

Early Apollo belt

Other regions

## EXPLORATION AND MINE PLANNING

Concepts are similar to large tonnage mineral sands dredging

Millions of tons/yr. of low grade material

Grade distribution/variation

Drill and sample operations

Large crater distribution

Large boulder distribution

Mine location

Determined by access to adequate reserves over time at

maximum grade with minimum of impediments to mining

Dump/tailings sites (if other than behind the miner)

## MINING

Concepts are similar to large tonnage mineral sands mining operations.

Mining Equipment

Million tonnes/yr.

Reliability/low maintenance/automation

Equipment mass (stability during mining)

Low Temperature (-50 C.) operation at mining face

Mining/Beneficiation/Processing

Combined/tandem/separated

Human presence requirements

Mine Plan

Operational Cycle Limitations

Power/maintenance/processing capacity

Large Boulders

Sensing/removal

Mining Support Base

Fixed/semimobile/mobile

Pilot Plant and Reserve Delineation

May be undertaken in conjunction with early base for O<sub>2</sub>

production for space transportation (see scenario of Schmitt, 1988, for example).

## BENEFICIATION

Concepts are related to mineral sand beneficiation Initial Separation of He-3 rich and He-3 poor Material

- Attritioning, grinding

- Screens, vibrators, material handling, and evolved gas

Preparation for Concentration of Retort Feed

- Grain size vs. electrostatic and/or magnetic susceptibility

- Middlings circuits

Concentration of retort feed

- Middlings circuit

Retort Extraction of gases

- Thermal power (solar vs. nuclear)/corrosion control/

- loss control (surface area about  $0.5 \text{ m}^2/\text{gm}$ )

- Excitation (sonic, microwave)

Transport of gases to processing plant vs. transport of retort feed to combined beneficiation and processing plant

## PROCESSING

Concepts similar to Hg ore and oil shale processing and crude oil refining.

Thermal Power

- Solar/Nuclear

Corrosion Control

Heat recovery

Condensation and separation of products

- Radiator size

- Lunar night operation

- He-3 separation on moon or on Earth

Storage

- Liquefaction of H<sub>2</sub> and He

Operational Cycle Limitations

- Power/maintenance/mining and beneficiation capacity



## SUPPORT

Concepts similar to North Slope crude oil production support  
Lunar base services

Habitat/food/landing and launch services/health maintenance/  
recreation/consumables production

Earth to Moon logistics

Spares/new construction/personnel replacement and additions

Moon to Earth Logistics

Moon to Space Logistics

Consumables export

Other Tenant services

Science

Propellant supply

Food production

Special site preparation (radiotelescope, mass drivers,  
habitats)

Settlement utilities and services (company town)

Possible tenant interactions

Public order

Lunar atmosphere

Seismic noise

## FINANCIAL

D/He-3 fusion development and lunar He-3 mining development must  
proceed in parallel

Management Organization

Operating Plan

Capital Acquisition and Cost

Budgeting

Product Pricing

Marketing

Margins controls

Personnel

Training

## Inventory Management

Imports (reliability of supply)

Exports (reliability of supply)

Discards

## Purchasing

## R & D and Exploration

## Environmental Control

## Economies of Scale

## Energy Pay-back

## Price of competitive energy sources

## CONCLUSIONS

1. Concepts that relate to economic geology of recovering He-3 from the lunar maria are not new to human experience.

### Space Operations

### Lunar Operations

### Large tonnage mining

### Beneficiation of low grade detrital resources

### Processing by thermal methods

### Logistical support of large scale commercial and scientific operations in remote locations

### Financial support and management of large scale commercial operations

2. A parametric cost and technology evaluation scheme, based on existing and future data, is required to qualitatively and quantitatively assess the comprehensive economic feasibility and Return on Investment of He-3 recovery from the lunar maria.

### Early outputs from this evaluation should include:

#### A. Candidate mining sites based on existing data

#### B. Additional earth-based studies and data acquisition required to further evaluate the candidate sites.

#### C. Types of data from additional automated or human exploration required to further evaluate the candidate sites.

- D. Types of data from engineering, financial, and mission planning activities required to further evaluate economic feasibility and ROI of lunar He-3 recovery.
  - E. Detailed scenarios for the initiation and operation of a lunar base or settlement for He-3 production.
3. Detailed plans for the research, development, and construction leading to commercial use of D/He-3 fusion technology are required in order to assess the economic, societal, and political value of He-3 supplies from the moon.

#### POLITICAL CONCLUSIONS

1. D/He-3 fusion and lunar He-3 mining will not become commercially viable or politically assured without the active and politically visible participation of large numbers of interested voters (2- 3000 per Congressional District) who support a "second to none" U.S. presence in space. A private sector effort should be organized for this purpose.
2. International cooperation, if any, should be based on user interests (such as the INTERLUNE concept described by Schmitt, 1988) rather than on one nation/one vote interests. Law of the sea/Moon Treaty international regimes should be avoided in order to not delay resource related activities indefinitely.
3. Interagency, cooperation (NASA, DOE, etc.) should be based on each agency's specific and long term commitment of both funds and personnel slots to a joint management team.
4. Informal coordination and discussion between all interested parties should continue to be encouraged and facilitated by NASA as has been done so well at this workshop.

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MINING FOR HELIUM - SITE SELECTION AND EVALUATION

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Part of the University of Wisconsin study of the feasibility of recovering He-3 from the moon is selection and evaluation of potential mining sites. Selection and evaluation are based primarily on four salient findings by the numerous investigators of lunar samples:

1. Regoliths from areas underlain by highland materials contain less than 20 wppm He.
2. Regoliths of certain maria or parts of maria also contain less than 20 wppm He, but mare regoliths at the Apollo 11 and Apollo 17 sites contain 25 to 49 wppm He.
3. The helium content of a regolith is a function of its composition. Regoliths with high He content are high in titanium content.
4. Helium is concentrated in the -50 micron size fractions of regoliths.

The first three findings are illustrated in Figure 1, in which helium content is plotted against  $TiO_2$  content for samples of highland and mare regoliths. Note that highland samples are low in both He and  $TiO_2$ . Mare samples, however, fall into two groups, one low in He and  $TiO_2$ , the other markedly higher in both. There is scattering of points, particularly at the high- $TiO_2$  end of the range, but a broad correlation of He content with  $TiO_2$  content is evident, and it seems clear that the  $TiO_2$  content of regolith can be used as a general guide in the selection of areas where the regolith contains 20 wppm of helium or more.

In site selection we are therefore concerned with the compositions of lunar regoliths, in particular with their titanium contents. It is widely accepted that compositions of mare regoliths are controlled by the nature of the underlying basalts from which the regoliths are largely derived. A number of types of basalts, differing in mineral and chemical composition, have been recognized by lunar investigators. In terms of titanium content, however, they fall into three general groups (1):

1. Very high-Ti basalts, containing 8% to 14%  $TiO_2$ . These were sampled by the Apollo 11 and 17 missions.
2. Low-Ti basalts, containing 1.5% to 5%  $TiO_2$ . Such basalts were sampled by the Apollo 12, Apollo 15, Luna 16, and Luna 24 missions.
3. Very low-Ti basalts, containing less than 1.5%  $TiO_2$ . They were recovered by the Luna 24 and Apollo 17 missions.

The distribution and extent of the three groups of basalts and the regoliths derived from them are the first basis for site selection and evaluation. Since sampling is thus far confined to very small areas of a few of a maria, information on distribution and extent is mostly from remote sensing of two general types - gamma-ray spectroscopy done by the Apollo 15 and 16 orbiter; and earth-based telescopic measurements of lunar reflectance. The results of both types of measurements have been calibrated, so far as possible, against lunar samples of known titanium content.

Figure 2 shows the results of gamma-ray spectroscopy as interpreted by Metzger (33). Coverage by the two orbiters was limited to two bands lying between 30 degrees N. and 15 degrees S. Two principal areas of high-Ti regolith are indicated, one the area of Mare Tranquillitatis with its extension northward into the Taurus-Littrow region of Apollo 17, the other a part of Oceanus Procellarum. Other interpretations of the gamma-ray data differ somewhat from the one shown here, but the broad picture remains the same.

There are various maps showing the distribution of high, low, and intermediate-Ti basaltic regoliths as interpreted from earth-based telescopic observations of reflectance at various wavelengths and combinations of wavelengths ranging from the ultraviolet to the near-infrared. Figure 3 was prepared from superposed ultraviolet negatives and infrared positives. It shows color groups of basaltic regoliths, with  $TiO_2$  values thought to be represented by the groups. High-Ti areas are shown in solid black. Mare Tranquillitatis again appears as high-Ti area extending into the Taurus-Littrow region. The map also indicates large areas of high-Ti regolith in the western Hemisphere, especially in Imbrium and Procellarum, but none of them has been sampled.

Quantitative spectral ratio mapping has been used by some investigators (2, 21, 24, 25, 28, 32). Compared to gamma-ray spectroscopy, spectral ratio mapping has the advantages of broader coverage of the lunar nearside and higher resolution. Resolution is important in site selection. On the basis of present information, Mare Tranquillitatis is of prime interest as a potential source of helium. However, a map by Johnson et al. (32), produced by imaging measurements of the 0.38  $\mu m$ /0.56  $\mu m$  spectral ratio, indicates that the  $TiO_2$  content of regolith in Mare Tranquillitatis varies from part to part of the mare. Figure 4 shows a region of high-Ti regolith separating two regions of lower-Ti regolith. We have no hard data for the  $TiO_2$  content of the latter two regions, but obviously they must be assigned a low priority in selection of sites for mining.

The scenario envisioned by the Wisconsin group calls for recovery of 244 metric tons of He-3 between 2015 and 2050. If we assume an average mining depth of 3 m, and an average He content of 30 wppm in regolith, then in Figure 5 Line A shows the areas that would contain the helium required during successive 5-year periods through 2050, and the total of those areas. Total recovery being impossible, line B shows the areas that would be involved if recovery were 80 percent. Line C shows the areas that would have to be mined if recovery were 60 percent, probably a more realistic figure. The diagram shows that mining areas of thousands of square kilometers must be delineated if the requirements of the scenario are to be met.

As indicated earlier, various investigators have demonstrated that helium is concentrated in the finer size fractions of regoliths. For the regolith sampled by Apollo 11, this relation is shown in Figure 6. Of the total helium in the regolith, 72.5 percent is in the  $<40 \mu m$  fractions, 80 percent in the  $<60 \mu m$  fractions. For recovery of helium, therefore, we have no interest in the coarse materials of regoliths. This, and considerations of ease of mining, means that mining areas should be as free as possible of blocks of rock and sizeable craters. Information on such features must be obtained from lunar photographs, from photogeologic maps, and from radar surveys that indicate roughness of the surface at various scales (2, 21, 31). Photogeologic maps can also shed light on variations in the composition of mare regoliths and can help in delineating areas that should be sampled.

The present study is necessarily a preliminary one. Data available have significant limitations. Only very small fractions of a few of the maria have been sampled. No area has been systematically sampled. Information on depth of regolith is limited. Remote sensing maps, both those based on gamma-ray spectroscopy and on reflectance measurements, have insufficient resolution from the standpoint of site selection. All remote sensing maps show large areas of intermediate-Ti regolith, but no such regolith has yet been sampled. Ash deposits are extensive in the Rima Bode and Sulpicius Gallus regions of the lunar nearside (29), and it is possible that black ash of high  $TiO_2$  content contains significant amounts of helium. However, nothing is known of its helium content in areas where it must have been gardened and exposed to the solar wind for long periods of time. These are serious deficiencies in present information. As a prelude to helium mining they must be remedied by systematic exploration and sampling of mare regoliths. Such work should have a high priority in future lunar missions.

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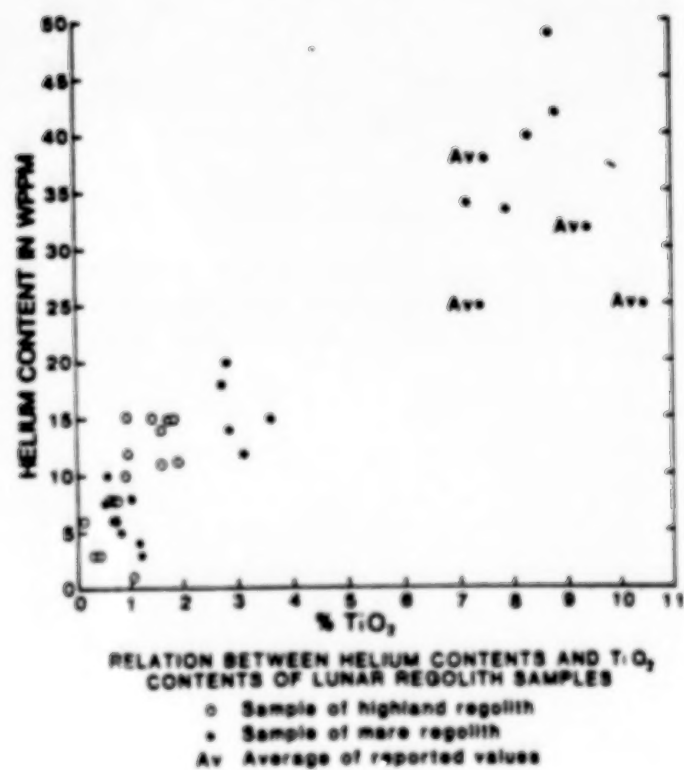


Figure 1. Data from references 3, 4, 5, 6, 7, 8, 9, 10, 11, 1, 13, 14, 15, 16, 17, 19, 20, 22, 23, 25, 26, 29.

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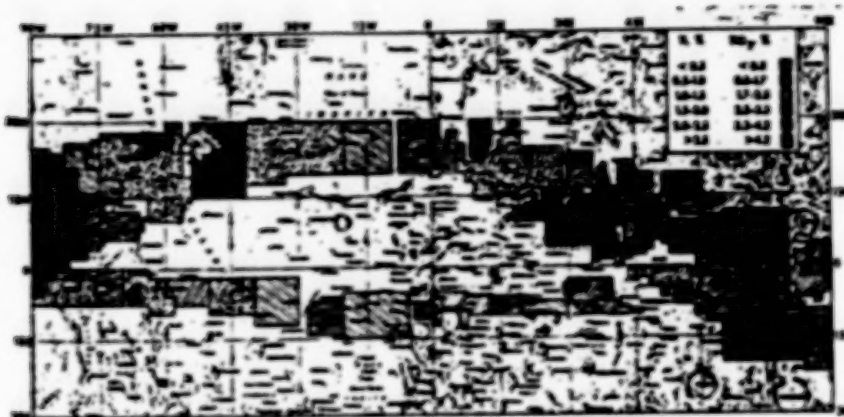


Figure 2. Map of the titanium content of the lunar regolith covering nearside regions overflowed by Apollo 15 and 16. From Metzger and Parker (33).

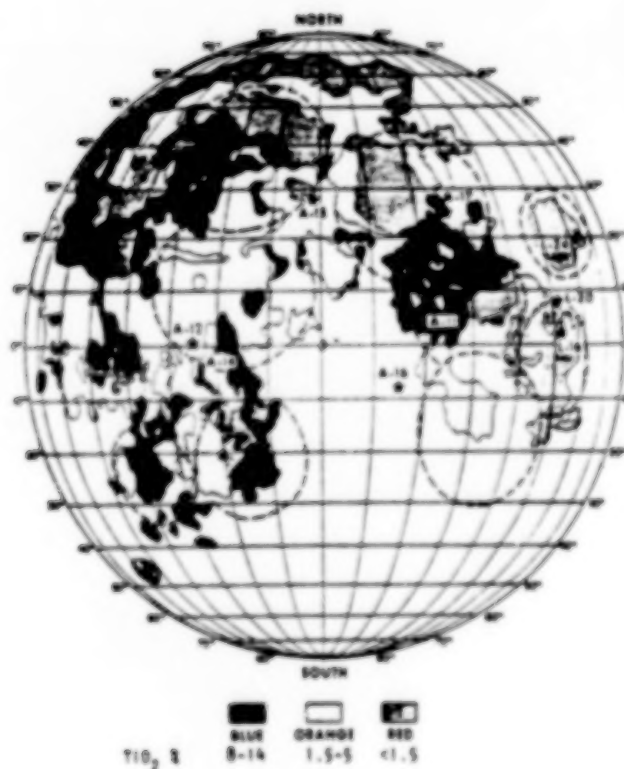


Figure 3. Color groups of mare regoliths and TiO<sub>2</sub> values thought to be represented by the groups. From Basaltic Volcanism (1).

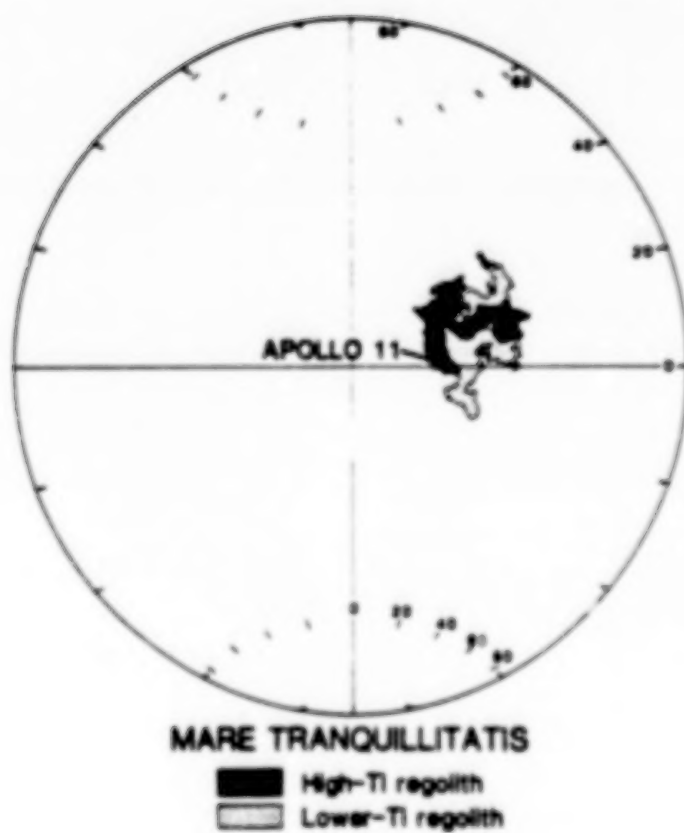


Figure 4. Regoliths of Mare Tranquillitatis.  
Based on map of lunar nearside by Wilhelms  
(29, Pl. 4A).

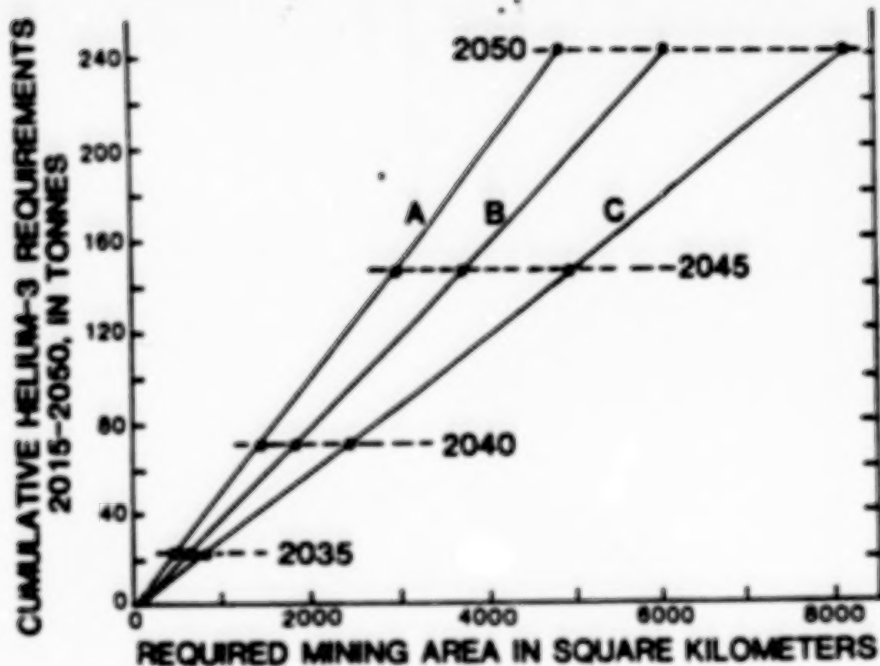


Figure 5. Required mining areas of lunar regolith, 2015 to 2050, assuming a mining depth of 3 m and an average of 30 wppm helium.

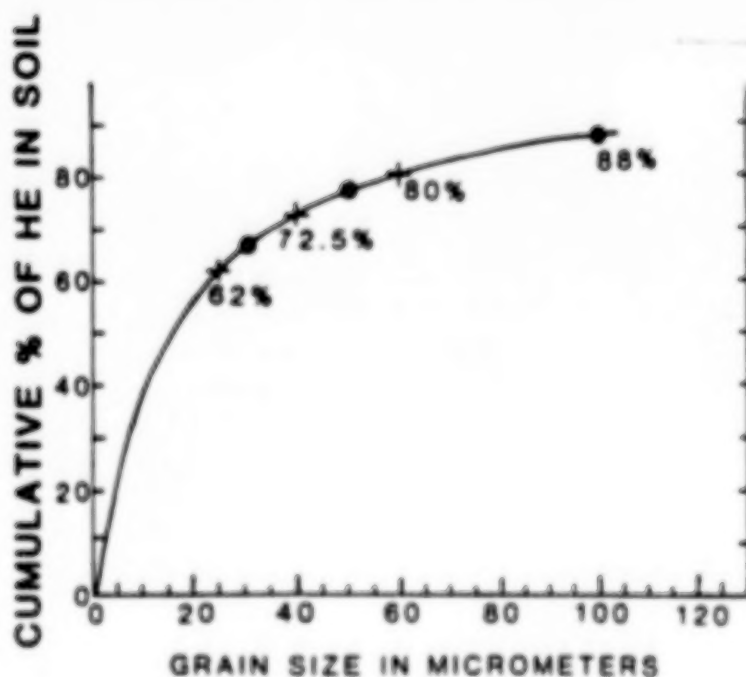


Figure 6. Percentage of total helium in relation to grain size in Apollo 11 regolith sample 10084. Based on Data from Criswell and Waldron (4) and Hintenberger et. al. (10).



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COMMERCIAL OBJECTIVES, TECHNOLOGY TRANSFER, AND SYSTEMS ANALYSIS  
FOR FUSION POWER DEVELOPMENT\*

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Fusion is an essentially inexhaustible source of energy that has the potential for economically attractive commercial applications with excellent safety and environmental characteristics. The primary focus for the fusion-energy development program is the generation of central-station electricity. Fusion has the potential, however, for many other applications. The fact that a large fraction of the energy released in a DT fusion reaction is carried by high-energy neutrons suggests potentially unique applications. These include breeding of fissile fuels, production of hydrogen and other chemical products, transmutation or "burning" of various nuclear or chemical wastes, radiation processing of materials, production of radioisotopes, food preservation, medical diagnosis and medical treatment, and space power and space propulsion. In addition, fusion R&D will lead to new products and new markets.

Each fusion application must meet certain standards of economic and safety and environmental attractiveness. For this reason, economics on the one hand, and safety and environment and licensing on the other hand, are the two primary criteria for setting long-range commercial fusion objectives. A major function of systems analysis is to evaluate the potential of fusion against these objectives and to help guide the fusion R&D program toward practical applications. The transfer of fusion technology and skills from the national laboratories and universities to industry is the key to achieving the long-range objective of commercial fusion applications.

**KEY WORDS:** fusion, fusion systems analysis, fusion applications, fusion technology transfer, fusion planning

## COMMERCIAL OBJECTIVES

### Electricity Production

The application of fusion that has received the most study is the production of electricity in a central-station power plant. Commercial objectives for fusion electricity production have the following aims: (1). Make fusion economically competitive with other forms of central-station power for the 21st century. (2). Exploit the safety and environmental advantages of fusion in plants that offer a very low risk to the public and to plant workers, as well as provide a very low risk of losing plant investment

costs. (3). Make the R&D costs for fusion an acceptable fraction of the potential benefit.

The key aspects of economic performance are low capital cost, short construction and licensing time, high availability, and low operating costs. These aspects are directly related to requirements on component performance, lifetime, repair time, and safety characteristics that affect licensing. Stringent requirements must be set in all of these areas. The most important areas involve component failure rates and repair times, because high availability must be maintained in fusion plants, which are capital-intensive. Another key objective is to provide a range of unit electrical power ratings in economically attractive plants.

The safety and environmental objectives stress inherent safety under all credible accident conditions. Inherent safety offers many potential benefits,

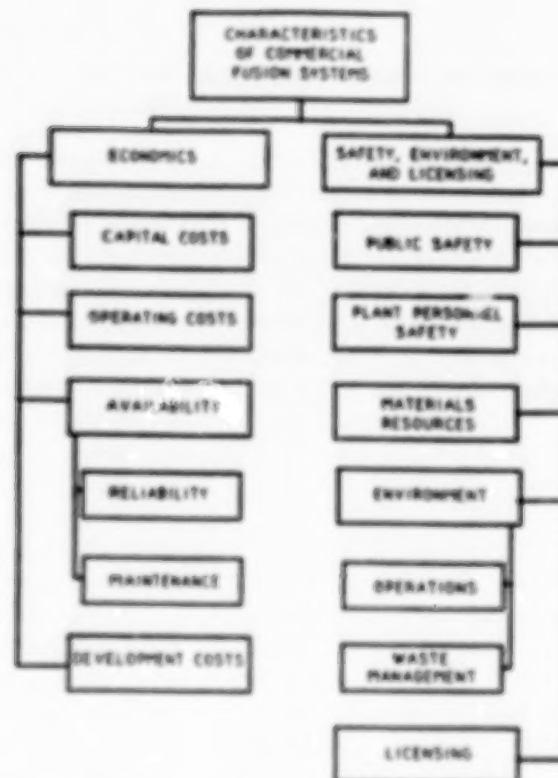


Fig. 1. Characteristics of commercial fusion systems.

Table 1. Economic Objectives, Attributes, and Target Values for Electricity Production

Program Element and Subelement	Objective	Attribute	Planning target
Economics	Minimize cost of product	Cost of electricity (mills per kilowatt-hour) evaluated by leveled costing, zero escalation, and inflation, in 1985 dollars	30-40
	Maximize investment protection	Cost of recovery from any fusion-core component or subsystem failure or accident, expressed as percent of original direct capital cost	5-15
		Time required for recovery from any accident (months)	3-9
Capital costs	Minimize capital costs	Total direct cost to construct plant (\$/kW <sub>e</sub> ) for a nominal 1000-MW <sub>e</sub> plant	~ 1000
Operating costs	Minimize operating costs	Cost to operate plant, expressed as percent of cost of electricity	< 5
Availability	Maximize availability	Percent of total time plant is available for full-power operations	~ 85
Development costs	Minimize development costs	Total projected development cost before first commercial order (\$10 <sup>6</sup> )	~ 20

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## Commercial Objectives, Technology Transfer, and Systems Analysis

including ease of licensing; elimination of high-cost, engineered safety systems; reduction in backfitting; lower cost for the balance of plant; and public acceptance. Inherent safety must be accompanied by very low normal emissions of hazardous materials.

The commercial objectives are set for a hierarchy of characteristics, as shown in Fig. 1. These objectives are given, along with attributes and target values, in Tables I and II.

### Fissile-Fuel Production

An application of fusion that may have economic potential is the cogeneration of both electricity and fissile fuels for later consumption in fission converter reactors (e.g., LWR or HTGR) that produce electricity or process heat. Fissile-fuel production has the following aims: (1). Make fusion-bred

fuels economically superior to mined and enriched uranium in the early decades of the 21st century. (2). Provide a source of affordable fissile fuel to support the domestic and international demand for nuclear power for the indefinite future. (3). Provide the technological basis and operating experience required to advance fusion technology to a level such that fusion electric-power generation will become an attractive alternative to conventional nuclear power.

The key aspects of economic performance are low capital costs, high fissile-fuel breeding, high availability, low operating costs, and low fuel-cycle costs. These aspects are directly related to requirements on component performance, lifetime, repair time, and safety characteristics. The most difficult problem areas are component failure rates and repair times. High availability is required in fusion plants because they are capital-intensive. For fissile-fuel breeding, the requirements on fusion performance

Table II. Safety, Environment, and Licensing—Objectives, Attributes, and Target Values

Program element and subelement	Objective	Attribute	Planning target
Public safety	Maximize public safety	Risk to public from accidents, expressed as percent of existing risk from all accidental sources	< 0.1
		Risk to public from routine operations, expressed as percent of existing risk from all routine sources	< 0.1
Plant-personnel safety	Maximize plant-personnel safety	Risk to plant personnel from occupational hazards and accidents, expressed as percent of risk from nonoccupational hazards	< 10
Materials	Maximize use of domestically available, abundant, or recyclable materials	For those elements for which fusion is the driver in domestic demand, recycle, expressed as percent of wastage per cycle	1-5, depending on element
		Procurement of no more than stated percent from nondomestic sources	< 20
Environment	Minimize thermal effluent from facility	Waste thermal effluent from facility, expressed as percent of gross thermal power	< 70
	Minimize long-term activation	Percentage of radioactive waste generated that qualifies for near-surface disposal, as defined in 10CFR61 or relevant extensions thereof	> 99%
		Dilution of used material to meet standards, expressed as factor increase in volume of disposed radioactive materials	< 10
Licensing	Minimize licensing time	Time frame during which licensing process is completed	Prior to or during construction



(relative to fusion-electric applications) are relaxed, because the fusion energy is multiplied severalfold in the blanket and because an additional product, fissile fuel, is produced. However, safety/environment/licensing issues may be similar to those encountered for fission plants.

### Synthetic-Fuel Production

Fusion energy could be a source of electricity and high-temperature process heat for the production of synthetic fuels. Hydrogen production by thermochemical water splitting or by high-temperature electrolysis has received limited study. The hydrogen produced can be used as a feedstock material to produce other fuels, such as methanol.

The advantage of fusion as the heat source for synthetic-fuel (synfuel) technologies stems from the deep penetration of the 14-MeV neutrons produced in the DT reaction. This penetration allows thermal decoupling of the high-temperature blanket from the fusion core. Such decoupling is not possible with combustion or fission heat sources.

The economic performance required of a fusion reactor for synfuel production is equal to or better than that required for central-station electricity production. Thus, most of the objectives defined for electricity are equally applicable to synfuels. The most important environmental objective is to keep the product (hydrogen or organic fuel) free of tritium contamination. The high mobility of tritium and its affinity to replace hydrogen in organic compounds will make achieving the required product cleanliness very difficult.

### Other Applications and Spinoffs

The three fusion applications described above are those that have been most extensively analyzed. Plausible conceptual designs have been developed for fusion systems to produce these products, and preliminary economic evaluations indicate that fusion has the potential to compete with alternative sources of these products in the planning time frame for commercial fusion applications. Other potential applications include transmutation of high-level wastes produced in fission reactors, production of radionuclides for commercial and medical applications, and production of special nuclear materials for military applications.

Preliminary analyses have been made of the use of fusion to transmute or "burn" actinide waste from fission reactors in order to reduce the amount of waste and its long-term toxicity. The prime concerns are economic feasibility and technical complexity.

An application area where fusion may have a significant advantage over alternative sources is the production of radionuclides. Fusion produces about five times more net neutrons per unit of thermal power than does fission, and these neutrons are of much higher energy (14 MeV, compared with 3 MeV for fission). This means that fusion can be a more prolific source of transmutation products than fission. Preliminary analysis of the production of cobalt-60 and other isotopes by fusion indicates that fusion reactors could easily satisfy future market requirements.

Finally, initial studies indicate that fusion reactors can potentially produce tritium and plutonium for military applications much more efficiently than can fission reactors. Many other potential fusion applications exist that have not yet been evaluated.

An important benefit from fusion is the "spinoff" of knowledge and technology to other fields. As the space program has amply demonstrated, when high-technology research and development is undertaken, products and applications result that are of significant benefit outside the immediate program. Fusion has already produced a positive benefit from spinoffs (see Table III). Additional spinoff benefits from fusion science and technology programs are expected.

### TECHNOLOGY TRANSFER

The DOE Magnetic Fusion Program Plan contains the following technology-transfer objective:

The technology transfer objective is to provide a range of options for private sector investment and commercial development of fusion. The establishment of the scientific and technological base for fusion requires industrial participants both to provide expertise in conventional components and to gain experience with the unique aspects of fusion science and technology. The necessary degree of industrial experience is best gained through the technical participation of industrial personnel in the state-of-the-art developments produced by the fusion program. A noteworthy aspect of this objective is that, through it, the fusion program will also serve as a stimulus to United States technological growth and the further training of scientists and engineers in industry.

## Commercial Objectives, Technology Transfer, and Systems Analysis

Table III. Spinoffs from Fusion Science and Technology Programs

Field	Spinoff
Computers	Cray timesharing-system software
Metal forming	Magneform system
Isotope separation	Plasma-separation process
Defense	Neutral- and charged-particle beams; high-power, high-frequency microwave sources and microwave transmission components
Welding	Refractory-armor materials and tiles, homopolar resistance welding
Magnets	Superconducting magnets for energy storage, materials processing, and medical applications

Table IV. Industrial Roles and Functions

Roles	Functions
Advisor	Support-Services Contractor Advisory Committees
Direct participant	Research and Development Materials Supplier Component Supplier and Manufacturer Subsystems Contractor Prime Contractor, Project Manager Facilities Operator Customer
Sponsor	Research and Development

This section describes how this DOE objective can be achieved. Industry has played and will play a variety of roles in the development of fusion energy. The more useful roles fulfilled by industry can be separated into three main categories. These categories, along with the principal functions performed in each category, are listed in Table IV. Each of these roles and the corresponding potential functions will be described. A technology transfer plan for industrial contributions in fusion is shown in Fig. 2.

### Industry as Advisor

The advisory role is filled frequently by corporate officials, who are asked to help assess various stages of program development and may serve on management boards of development projects. The principal benefit expected from the advisory role is the development of appropriate program goals. (This role is discussed below.)

#### Support Services

Industry acts as a support-services contractor when it assigns individuals or small groups of indi-

viduals to work in direct support of a manager at DOE or at a national laboratory. In such an arrangement, the customer benefits by acquiring immediately needed skills and having a long-term personnel commitment. Industry benefits by acquiring knowledge, contacts, and income.

#### Advisory Committees

Utilities, as well as industry, can provide members of their technical staffs to serve on technical committees assigned to carry out specific tasks. This participation serves to facilitate development of program goals and provides useful feedback regarding program direction.

### Industry as Direct Participant

A number of studies have been conducted to examine the characteristics of research programs that led to the successful commercialization of new technologies. A common characteristic among those technologies was the early involvement of the ultimate user. Therefore, it is important both to the user and to the national program to include early participation of the user at all phases of the program.

To become major participants in the fusion program, industrial executives must understand and identify with near-term program objectives. The program objectives must be developed in conjunction with the ultimate users, if they are expected to become involved early. One near-term goal, essential to the success of fusion, is the resolution of environmental and safety issues, which have proven to be a major stumbling block for fission.

Direct participation requires a corporate commitment of financial and manpower resources to

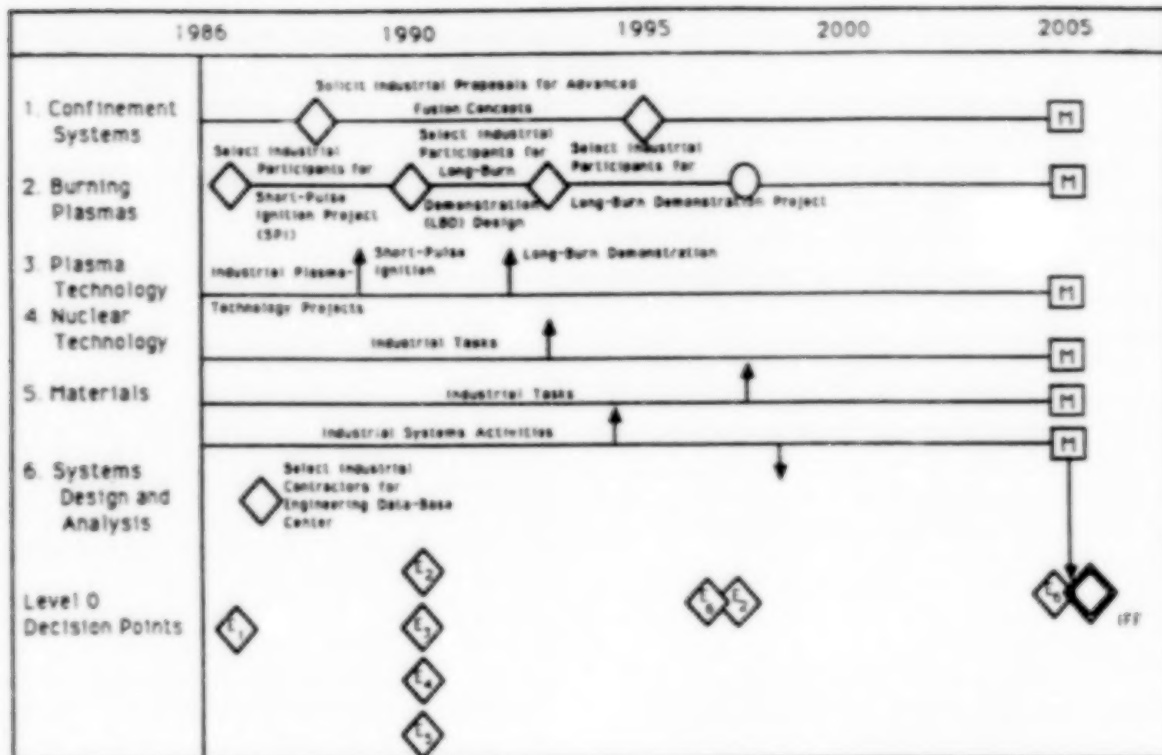


Fig. 2. Logic diagram for technology-transfer plan.

perform fusion work. This type of participation can take a variety of forms; the more notable functions, listed in Table IV, are discussed.

#### Research and Development

Private companies with unique ideas should be able to compete for funding when, after peer review, such support is technically warranted. The fusion program should make full use of novel ideas and approaches conceived in all sectors of the society, including individuals, national laboratories, universities, and private companies.

#### Materials Supplier

Materials used for commercial application will require a well-documented history for quality-assurance/quality-control (QA/QC) purposes. As the program enters the commercialization phase of fusion development, detailed engineering specifications will be needed.

#### Component Supplier and Manufacturer

Industry acts as component supplier or manufacturer when it supplies an off-the-shelf component or when the customer has build-to-print requirements. Industry also frequently designs and manufactures components to customer-supplied specifications. Increasingly, manufacturers will have to take on the job of fabricating fusion-specific components, subsystems, and (eventually) complete reactor systems.

#### Subsystems Contractor

Industry acts as a subsystems contractor in situations where the customer has defined a scope of work and has assigned to a company the responsibility for performance. This is a most desirable form of industrial participation. The customer benefits by having corporate commitment to the project, and industry benefits by being able to fully exercise its managerial and technical skills through a task assignment where it can bring to bear its background and experience.



## Commercial Objectives, Technology Transfer, and Systems Analysis

### *Prime Contractor, Project Manager*

Industry acts as prime contractor or project manager when it is directly responsible to a customer (e.g., DOE, a national laboratory, or eventually, an electric utility) for defined aspects of management, engineering, fabrication, and installation of a product, such as a fusion device or power reactor. An architect-engineer usually represents the client for engineering, procurement, and construction. However, the manufacture of the steam-supply system is usually carried out by separate companies. The industry roles that will emerge for fusion can only be developed by having experienced companies participate in the program. Preparing companies for these roles should be an important component in the fusion program.

### *Facilities Operator*

Many companies are in the business of operating manufacturing plants, chemical plants, communications networks, and other sophisticated operational activities. To compete in the marketplace, these companies must also mobilize and manage the personnel logistics and training required for facilities operation. Industrial companies can operate fusion equipment that they or others fabricate. This can be an important learning experience and can help prepare the companies for more important roles in the future and for direct participation in the development of fusion power. This is particularly true for those fusion experiments that involve technology development.

### *Customer*

It is important for potential customers to interact with the developers of fusion to ensure that the final product is one that is acceptable for commercial use. Customers must be fully knowledgeable about the scientific and technological questions to be addressed in determining design trade-offs. Companies that deal with customers must be prepared to stand behind their products and services with performance guarantees.

### *Industry as Sponsor*

Sponsorship includes contributions of direct funds, labor, or both. This form of participation has

existed since the 1950s, albeit on a small scale, and is continuing now. Industrial sponsorship of fusion R & D includes the direct support of university research by utilities. Indirect utility support has also been provided through the Electric Power Research Institute (EPRI).

## SYSTEMS DESIGN AND ANALYSIS

The systems design and analysis area supports major fusion program evaluation and decision points and guides fusion research and development toward practical products. The objectives of the activities in this area should be: (1) to ensure the development of practical fusion applications, (2) to complete preconceptual designs of major fusion facilities, (3) to analyze critical issues and optimize development paths, (4) to identify and implement necessary safety, environmental, and licensing features for fusion development, (5) to plan and execute necessary research and development for remote technology equipment, and (6) to evaluate the potential of alternative (non-DT) fuel cycles. The major systems activities are characterized in Fig. 3.

Systems design and analysis activities provide the fusion program with important tools, data, and perspective. Activities include the identification and resolution of critical issues that involve the interaction of plasma physics and technology, the maintenance of an engineering data base, and the setting of subsystem objectives based on identification of desired economic and safety/environmental characteristics of commercial fusion applications.

A recent accomplishment of these activities is the preconceptual design of the proposed short-pulse ignition experiment. The integrated physics and engineering effort involved in that high-field design showed that a low-cost, short-pulse ignition experiment was possible. This conclusion had not been widely accepted by the fusion community a few years earlier. The systems activities have also provided a key basis for international collaboration through the International Tokamak Reactor (INTOR) program. Guidance from systems studies also has had a major impact on programmatic directions in such areas as steady-state current drive and high-beta tokamak operation. Design studies of reactors based on advanced fusion concepts have also guided research programs for these concepts.

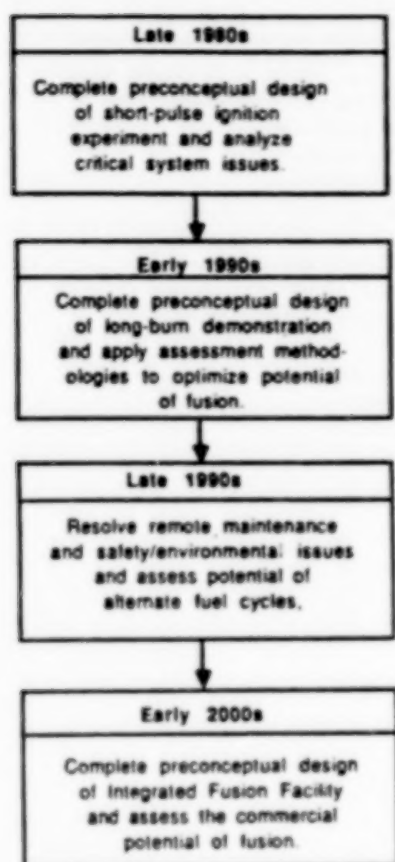


Fig. 3. Characterization of tasks for systems design and analysis.

Commercial fusion facility designs are important, particularly at this early stage of fusion development, to help identify necessary R&D program goals. The design studies are essential for guiding fusion R&D, and they provide a focus for the fusion program—namely, the development of useful products. The designs highlight the importance of good safety and environmental features, combined with acceptable costs.

Through design studies, system requirements are identified and the research and development needed for the fruition of fusion applications is forecast. For any given confinement scheme, the design activities ensure that all subsystems can be integrated within the constraints imposed by materials, technology, and physics to produce a system that is economically attractive and technologically feasible, while simultaneously maximizing safety and minimizing environmental effects. Depending on the confinement scheme being considered, these studies range from simple scoping analyses to detailed, multiyear preconceptional designs using sophisticated models.

Systems studies will provide important programmatic guidance in the preconceptional design of the device to produce a long-burn demonstration. The long-burn demonstration links broad national and international interests in fusion development. There is a spectrum of possibilities for long-pulse ignited devices, with a substantial variation in cost and technology requirements. The fusion program must find the most attractive design concept.

Another important function of systems activities is to search for development paths that have test-facility requirements that minimize the cost and risk of fusion development and compress the schedule. Test facilities should be capable of relatively rapid construction and very reliable operation. This is a very difficult issue, requiring contributions from people who have special expertise in global systems analysis.

Systems design and analysis covers a broad array of conceptual studies and facility designs, defines and maintains a listing of subsystems and component objectives for commercial and integrated test fusion reactors, relates these objectives to the objectives of specific science and technology programs, and assists in the optimization of program-implementation strategies. Systems design and analysis also treats the programs required (1) for developing remote technology equipment and (2) for developing fusion concepts based upon non-DT fuel cycles.

The systems design and analysis area should include the following program elements: (1) applications, economics, and technology transfer, (2) fusion test facilities, critical issues, and development pathways, (3) safety, environment, and licensing, (4) remote technology, (5) alternative fuel cycles.

A further breakdown of these program elements (discussed below) into subelements is given in Table V. A logic diagram is shown in Fig. 4.

#### *Applications, Economics, and Technology Transfer*

This program element includes activities in commercial-reactor preconceptional design, development of a range of fusion applications, development and application of methods to analyze the economic potential of fusion applications, and studies of factors affecting availability of facilities. It also provides for studies to identify the appropriate roles and timing for industrial participation in fusion R&D activities and the process of transferring the technology to industry. The milestones for this element are



## Commercial Objectives, Technology Transfer, and Systems Analysis

Table V. Systems Design and Analysis Program Elements and Subelements

Program elements	Subelements
Applications, economics and technology transfer	Commercial-reactor preconceptual design Applications studies Economics analysis Availability analysis Technology-transfer studies
Fusion test facilities, critical issues, and development pathways	Fusion test facilities preconceptual design Critical-issues analysis Engineering-data-base assessment Development-pathways analysis
Safety, environment, and licensing	Safety Environment Licensing
Remote technology	Program plan Concepts Equipment development Applications
Alternative fuel cycles	Confinement systems and burning plasmas Plasma technology Nuclear technology and materials Systems design and analysis

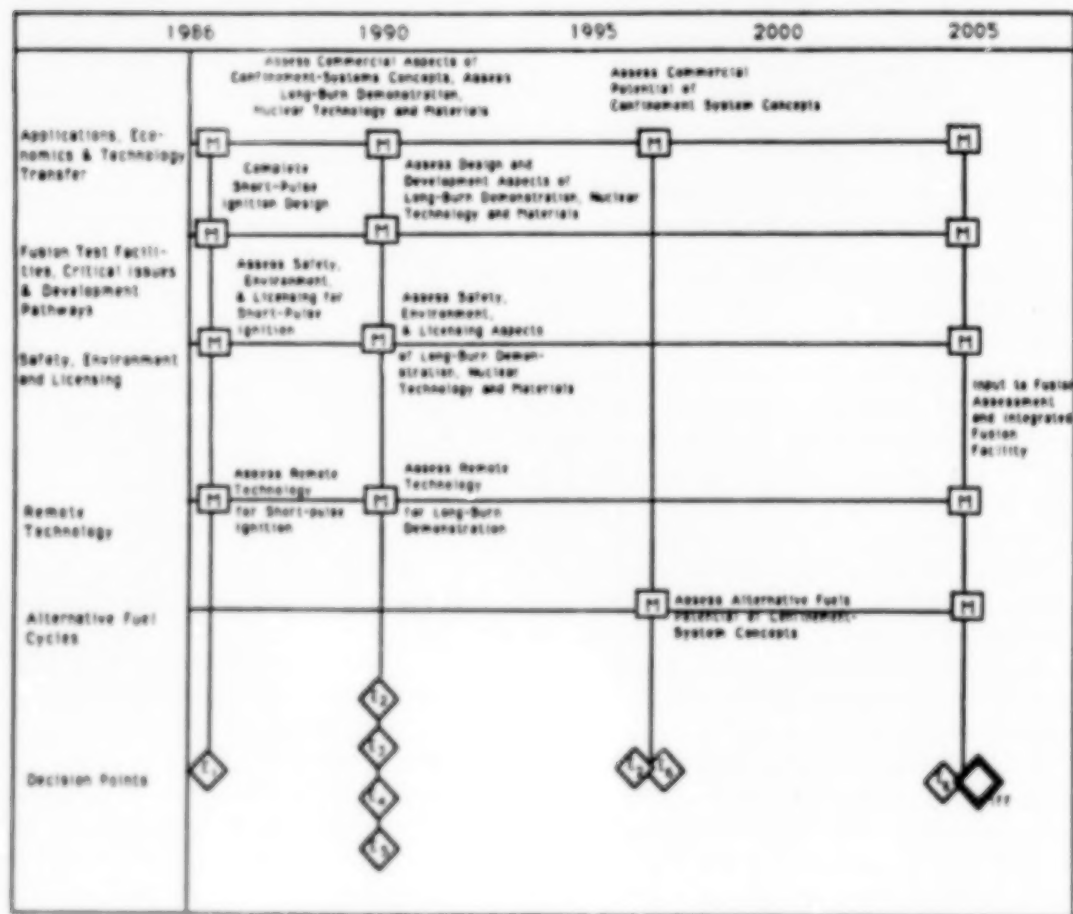


Fig. 4. Logic diagram for systems design and analysis.

to use the methods and data from these studies in reaching major program decisions.

#### *Fusion Test Facilities, Critical Issues, and Development Pathways*

This program element includes, in part, preconceptual designs of fusion test facilities, such as the short-pulse ignition experiment, the long-burn demonstration, and the integrated fusion facility. Milestones are established to provide the data to support those program decisions (see Fig. 4). This program element also provides for ongoing analysis of critical issues, including the assessment of systems issues arising from physics/technology interfaces identified in design studies. This element also provides for the establishment and maintenance of an engineering data base for component fabrication and design standards and includes development-pathways analysis, to develop and apply methodologies for estimating the time, risk, and cost impact of alternative technical options for fusion power development.

#### *Safety, Environment, and Licensing*

This program element is focused on the identification of critical fusion safety and environmental issues and on providing (1) experimentally verified methodologies for analysis, assessment, and resolution of these issues; (2) a technical basis for safety and environmental improvements in fusion reactor designs; and (3) a technical foundation and recommended strategies for licensing of commercial fusion reactors. The major milestones are timed to provide information to be used in making major program decisions.

#### *Remote Technology*

This program element includes activities aimed at developing the necessary design inputs, equipment, and procedures to support availability goals for a sequence of more ambitious test facilities, leading eventually to commercial plants. While substantial advances in remote technology can be anticipated independently of the fusion program, many aspects will be unique to fusion. The major milestones in this area are to provide the necessary remote-technology readiness needed for the decisions to build major fusion facilities (such as the short-pulse ignition ex-

periment, the long-burn demonstration, and the integrated fusion facility) and to provide special-purpose equipment for these facilities.

#### *Alternative Fuel Cycles*

This program element includes the analysis of the potential of fusion fuel cycles other than the primary deuterium-tritium (DT) option. Operation with a fuel cycle other than DT could potentially reduce significantly the constraints on fusion-reactor design by eliminating the requirement for a tritium-breeding blanket. However, substantially improved values of beta and density-confinement-time product are necessary, compared with those required for DT operation. In addition, devices of larger size, stronger magnetic field, or both may be required. A variety of R&D activities important to the assessment of alternative fuel cycles is required. The results of these activities are not projected to influence a major program decision until the late 1990s.

### **APPLICATIONS, ECONOMICS, AND TECHNOLOGY TRANSFER**

This program element consists of the following five subelements: (1) commercial facilities preconceptual design, (2) applications studies, (3) economic analysis, (4) availability analysis, (5) technology-transfer studies.

#### *Issues, Objectives, and Attributes*

The issues associated with the program element for applications, economics, and technology transfer are as follows: (1) The full range of potential commercial applications for fusion science and technology must be identified. The most likely application and the one that has received the most study is the generation of electricity; however, a number of other potential applications must be considered. (2) Preconceptual designs of potential commercial facilities must be performed now (and updated frequently), so that systems-related issues important to the design of attractive end products likely to affect near-term R&D programs will be appropriately identified. (3) Fusion research and development is carried out primarily in national laboratories and universities at present, but the skills required to commercialize fu-

## Commercial Objectives, Technology Transfer, and Systems Analysis

Table VI. Objectives and Attributes for Applications, Economics, and Technology Transfer Program Element

Objective	Attribute	Planning target
Maximize number of fusion applications.	Number of potential applications with competitive economic and safety/environmental features	At least three
Maximize attractiveness of commercial fusion applications	Number of designs that meet economic and safety/environmental targets for each application	At least three
Optimize industrial participation in fusion program	Preparation of technology-transfer plan	Complete plan
Develop skill in projecting fusion economics	Preparation and standardization of economic models	Complete models
Maximize plant availability	Development of model and data base to analyze plant availability	Complete model and data base

sion must eventually be based in industry. (4) Perspective is required on the potential economics of fusion applications because fusion must compete with other technologies in the commercial marketplace. Plant availability is a critical factor in economic analysis. (5) Data, approaches, and methodologies are needed to establish a basis to achieve acceptable availability in fusion facilities.

The objectives, associated attributes, and proposed planning targets required to resolve the above issues are listed in Table VI.

### Program Logic

The logic diagram for this program element is shown in Fig. 5. The program logic is discussed below.

### Commercial-Reactor Preconceptual Design

This design effort includes conceptualization of commercial fusion facilities. Design activities are carried out for all fusion confinement concepts. The insights gained from these design activities are used to guide the science and technology programs and to assist with major program evaluations. Studies may be performed at varying levels of detail, as appropriate. For example, concepts with no direct experimental basis would be limited to scoping studies to assess their potential; preconceptual designs based on physics scaling and general reactor modeling

would be carried out for concepts with some small-scale experimental verification, and concepts having a major experimental base would undergo detailed preconceptual engineering design.

### Fusion Applications Studies

These studies are carried out in three areas: (1) continued assessment of the supply, demand, and cost of electricity from fusion; (2) investigation of fissile-fuel and nuclear-materials breeding; and (3) exploration of other nonelectric fusion applications.

The study of fissile-materials production would provide a basis for the technical evaluation of using fusion as a source of neutrons for such applications. An updated evaluation of fast fission hybrids should be made that incorporates the new safety and fuel-cycle ideas developed in recent years as part of the fission-suppressed hybrid designs. These ideas could lead to a significant improvement in the attractiveness of fast fission designs. Low- $Q$  fusion reactors should be included in hybrid-system designs. These evaluations would contribute to the decision on a reference fusion breeder design. In parallel with the design of the reference fusion breeder, fuel cycle and reprocessing studies and deployment and development studies should be performed. The results of these studies would provide the basis for an evaluation of the technical, economic, safety, and environmental characteristics of the fusion breeder for input into the integrated fusion facility decision and the overall assessment of fusion.

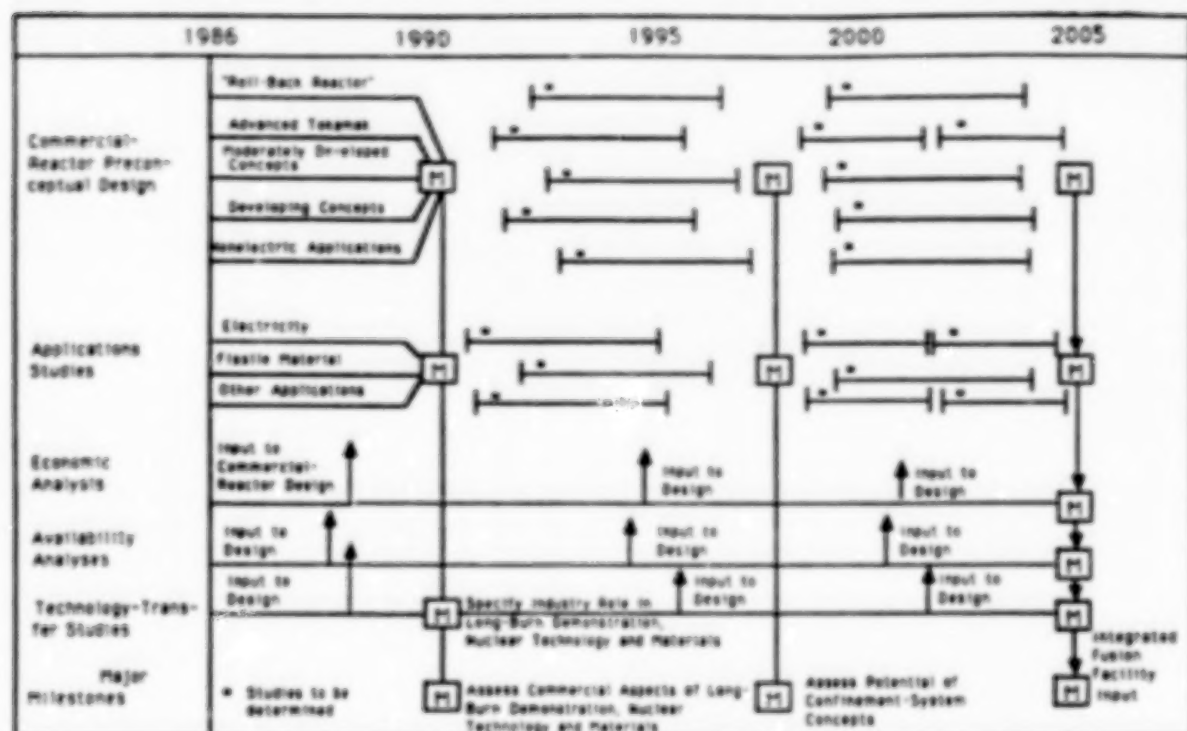


Fig. 5. Logic diagram for applications, economics, and technology transfer.

The other potential applications of fusion should be studied to provide a thorough assessment of the capability of fusion to produce a wide variety of products other than electricity and nuclear fuel. Fusion has the potential to produce hydrogen and other nuclear materials and chemical products, to "burn" nuclear and chemical wastes, to produce useful radioisotopes for food preservation and medical applications, to perform radiation processing of materials, and to provide space power and space propulsion. Still other applications may be possible. These studies will provide a preliminary assessment of the many potential applications of fusion and identify potential new ideas. These new ideas will be compared with applications that have already been evaluated. The results of small-scale experiments to verify the nuclear and chemical processes required for some applications will be considered in these studies. This task will culminate in an assessment of the potential of fusion to produce useful products in addition to electricity and fissile fuel. This assessment will produce valuable information for the overall assessment of fusion and for the decision whether to proceed with an integrated fusion facility.

#### *Economics Analysis*

This task consists of (1) developing and applying methodologies for estimating the costs of fusion products, (2) maintaining a cost data base, and (3) assessing the impact of development costs on fusion economics.

#### *Availability Analysis*

This task consists of (1) developing and applying methodologies to predict the availability of commercial fusion facilities and fusion test facilities, (2) establishing and maintaining a component reliability/maintainability data base, and (3) recommending design and/or operational modifications to improve facility availability.

#### *Technology Transfer*

This activity consists of studies to analyze and apply procedures for identifying appropriate industrial roles in fusion R&D activities. Results of



## Commercial Objectives, Technology Transfer, and Systems Analysis

these studies will be available as input to major program decisions and for incorporation into agreements on international collaboration.

### FUSION TEST FACILITIES, CRITICAL ISSUES, AND DEVELOPMENT PATHWAYS

This program element consists of the following four subelements: (1) fusion test facilities preconceptual design, (2) critical-issues analysis, (3) engineering-data-base assessment, (4) development-pathways analysis.

#### Issues, Objectives, and Attributes

The issues associated with this program element are as follows: (1) Timely preconceptual design studies of required fusion test facilities must be available to support major program decisions and discussions on international collaboration. These studies are also critical to development-pathways analysis. (2) Many critical technical issues involve the interaction of plasma physics and one or more technology components and, thus, would not necessarily be addressed by the component-development or science programs. (3) A continuing formal effort is required to optimize the technical program, because a large number of optional technical pathways exist, each with its associated cost, schedule, and risk.

The objectives and associated attributes required to resolve these issues are listed in Table VII.

#### Program Logic

The logic diagram for this program element is shown in Fig. 6; program subelements are discussed below.

#### Fusion Test Facilities Preconceptual Design

Preconceptual design activities are carried out for test facilities having a fusion plasma core. The activities include support for the short-pulse ignition experiment and a long-burn demonstration, as well as as possible engineering or materials test reactors or other integrated fusion facilities.

Preconceptual design studies typically are performed to identify promising embodiments of a given confinement concept to satisfy the fusion test facilities missions and objectives. Each study evaluates candidate options at a scoping level, makes a choice among the options that becomes a baseline design, and then develops the physics and component engineering of all the major systems and subsystems to a depth sufficient to establish feasibility, R&D needs, and performance. Companion activities are performed that include establishment of design and construction schedules, safety and environmental

Table VII. Objectives and Attributes for Fusion Test Facilities, Critical Issues, and Development-Pathways Program Element

Objective	Attribute	Planning target
Design fusion test facilities	Number of designs completed or under way	At least four
Minimize cost of fusion test facilities	Capital cost of any individual test facility, expressed as percent of annual magnetic-fusion budget	Less than 20%
Maximize resolution of systems-based critical issues	Number of design studies formally reviewed and critical issues analyzed	All
Minimize cost, schedule, and risk of fusion-energy development	Preparation of methodology for performing development-pathways analysis	Complete model
Maximize excellence of engineering in fusion facilities	Establishment and maintenance of engineering data-base from fusion and fusion-related experience	Establish engineering-data-base center



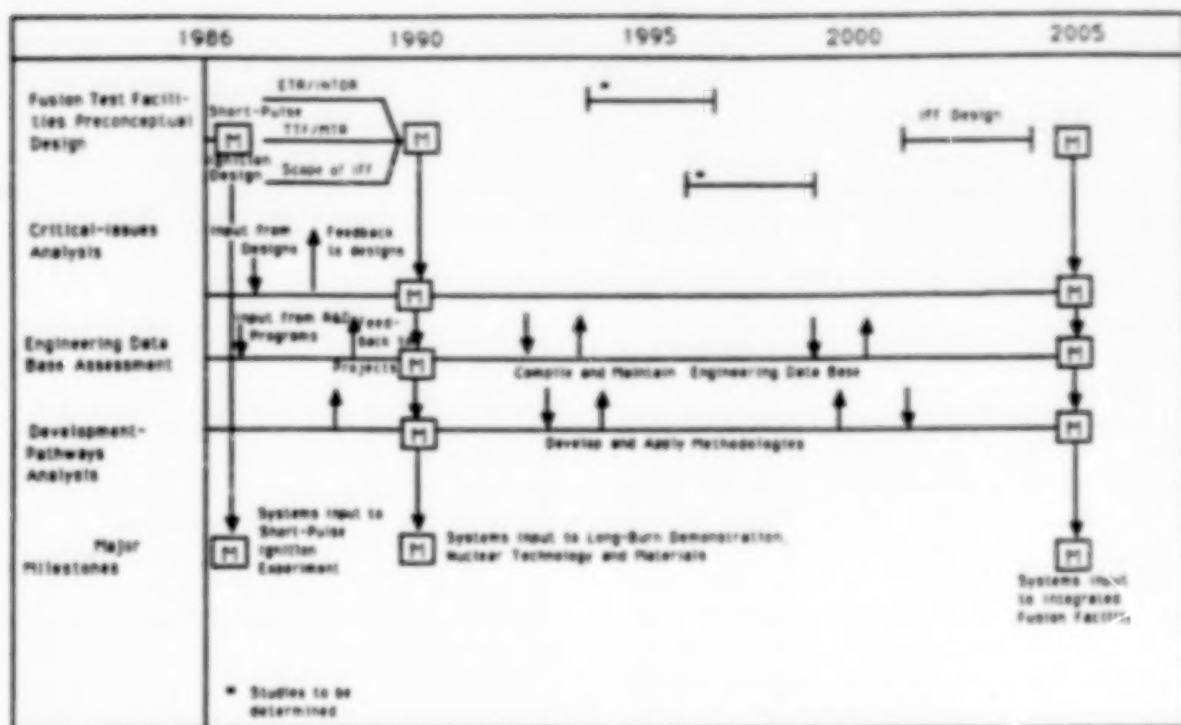


Fig. 6. Logic diagram for fusion test facilities, critical issues, and development pathways.

evaluations, siting evaluations, conventional facilities needs, and preparations of comprehensive cost estimates.

Completion of preconceptual design studies for major fusion test facilities is a significant systems design and analysis activity. Such studies require an integrated project team with physics and technological expertise and project-oriented tasks and milestones. The output of such studies provides the program with the basis for decisions to launch major construction projects.

#### Critical-Issues Analysis

This task consists of reviews of all conceptual-design reports and other systems studies to identify critical technical issues that involve the interaction of several aspects of plasma physics and fusion technology and the analyses of these issues. The activity investigates innovative solutions and identifies required R&D. Some technical issues, such as impurity control and transient electromagnetics, can be properly addressed only in a systems context. Basic information is developed in the physics and technology

R&D programs, but the synthesis of this information into workable solutions requires systems analysis.

The study of critical issues may be broken down into two categories: (1) feasibility analysis and optimization and (2) innovative-solutions studies. Feasibility analysis and optimization consists of in-depth analyses of leading candidate systems (e.g., the poloidal divertor for impurity control). This activity consists of model development and verification, analyses to determine performance limits, and detailed analyses to optimize design parameters. Such studies should produce an understanding of how the system works, verification of calculational tools, and guidelines for design optimization. These results are important for the preconceptual design activities of both test facilities and commercial facilities.

Innovative-solutions studies are intended to find better or simpler solutions to critical systems issues. For example, a scheme for cooling the plasma edge could allow a simpler limiter to replace the divertor for impurity control. The results of such studies provide input to the feasibility analysis and optimization studies and also provide guidance for innovative conceptual-design studies. These results will also be

integrated into the science and technology R&D programs.

#### *Engineering-Data-Base Assessment*

This activity involves the compilation and evaluation of engineering information that will aid the design, construction, and operation of future fusion facilities. As fusion research moves toward the development of more engineering-oriented fusion devices and ultimate commercialization, an ongoing program will be needed to develop and maintain a data base of engineering practices, experiences, and needs. This compilation should be based on knowledge and understanding obtained from the design, construction, and operation of previous and existing fusion devices; on a compilation of perceived engineering-related needs for future fusion devices; and on engineering advances made in advanced technologies related to fusion. Development and maintenance of such an engineering data base will enhance the ability of the fusion program to incorporate the best components, systems, and engineering practices into future fusion devices.

#### *Development-Pathways Analysis*

This activity consists of developing and applying methodologies for assessing the cost, risk, and schedule impacts of differing approaches to fusion development. The methodologies incorporate such factors as technical uncertainties and the size, cost, and number of needed test facilities. The technique will incorporate standardized methods for comparing different concepts and different potential applications. An important objective is to identify pathways that lead to useful commercial products while minimizing development times and costs.

### **SAFETY, ENVIRONMENT, AND LICENSING**

The safety, environment, and licensing program element consists of the following three subelements: (1) safety, (2) environment, (3) licensing.

This program element is aimed at performing the experiments and analyses required to develop a quantitative understanding of fusion safety and environmental issues and to provide the needed safety, environment, and licensing input. This input will

affect (1) the selection and design of the short-pulse ignition experiment, (2) the long-burn demonstration, (3) fusion-technology separate effects and integrated testing, (4) fusion technology and materials testing in a fusion environment, and (5) the overall evaluation of the potential for commercial fusion and the decision on an integrated fusion facility.

#### **Issues, Objectives, and Attributes**

The primary issues in the safety, environment, and licensing program element are associated with the radioactive inventories that will result from the operation of fusion reactors. These inventories can vary widely, depending on the fusion fuel cycle (e.g., DT, DD, or D<sup>3</sup>He) and reactor materials chosen. For example, a DT-burning fusion reactor with a stainless steel structure will contain approximately  $10^9$  Ci of activation products per gigawatt thermal ( $10^9$  Ci/GW) and approximately  $10^9$  Ci of tritium. Regardless of the choices of fuel cycle and materials, protection of the health and safety of the general public and plant operating personnel must be ensured during normal operation and during accident conditions. Fusion plants must also have acceptable environmental features, and the licensing of fusion plants must be accomplished in an efficient manner. The primary issues are as follows:

1. Protection of the general public and plant operating personnel must be provided during all normal and accident conditions that could occur at a fusion plant. Whenever possible, this protection should be provided by having plants that are inherently safe (having passive safety features rather than extensive engineered safeguards). Research to resolve this issue should focus on the presence and potential release of radioactivity in the fusion plant.

2. Safety-analysis methodologies must be developed for analyzing the potential safety and environmental impacts of fusion plants. These methodologies must be adequately verified by comparison with data from separate-effects and integral systems tests. Results obtained by use of these methodologies must be realistic and have quantifiable uncertainties.

3. Fusion plants must be environmentally benign and comply with environmental criteria acceptable to regulatory agencies and the general public. For example, the U.S. Environmental Protection Agency's standards for air and water quality must be followed.

In terms of waste management, the fusion community should adopt the goal that fusion radioactive wastes be amenable to disposal by shallow land burial, as specified in 10CFR61. Also, materials-utilization strategies must be developed, including recycling, so that implementation of a fusion economy does not strain the natural resources available for fusion-plant deployment.

4. A rational, efficient licensing system must be developed for commercial plants. Ideally, licensing should not constitute a significant cost of installing a

fusion plant, and the licensing activity should be easily accomplished within the time required to physically construct the plant. At the present time, a licensing approach based on risk-based safety goals and the risk-assessment methodology appears to be the most rational approach. With such an approach, the risks from fusion can be placed in context with other societal risks.

The objectives and their associated attributes needed for the resolution of these issues are listed in Table VIII.

Table VIII. Objectives and Attributes for Safety, Environment, and Licensing Program Element

Objective	Attribute	Planning target
Maximize safety of general public during normal operation and during accidents	Risk to general public, expressed as an incremental increase in existing risk from all routine and accidental sources	Less than 0.1% per individual
Maximize plant personnel safety	Risk to plant personnel, expressed as a percent of risk from nonoccupational hazards	Less than 10%
Maximize quantitative understanding of safety aspects of fusion system	Methodologies developed for assessing safety consequences of fusion power	Develop and verify models, with quantifiable uncertainties in calculated results
Maximize inherent safety of fusion	Number of prompt fatalities in general public, calculated as a result of severe but credible accidents, with passive safety features	Zero
Maximize understanding of fusion radioactive wastes produced	Methodologies developed for calculating quantity of radioactive waste to be handled for each radioisotope	Develop and verify models, with quantifiable uncertainties in calculated results
Minimize high-level radioactive wastes from fusion systems	Percentage of radioactive wastes from fusion plants that can qualify for near-surface burial, as defined in 10CFR61	> 99%
Maximize use of abundant or easily recyclable materials	For materials with near-term supply limitations, percentage of wastage per recycle	Less than 5%
Minimize impact of licensing activities on cost of fusion power	Percentage of cost of fusion power that can be attributed to licensing activities and delays	Less than 5%
Minimize licensing time for fusion plants	Time frame for completion of licensing process	Within time required to physically construct plant
Maximize use of probabilistic risk-assessment techniques in fusion licensing	Capability developed to implement probabilistic risk assessment for fusion systems	Develop methodologies, gather appropriate data base, and obtain approval of safety goals

## Program Logic

The logic diagram for this subelement is shown in Fig. 7. Figures 8 and 9 show the three logic diagrams for the safety subelement and combined environment and licensing subelements, respectively. The implications of these figures are discussed below.

The primary activities involved in the safety subelement are: (1) to develop and apply methodologies for assessing accident consequences and (2) to develop and collect the data base necessary for the verification of these methodologies. Research is focused on the safety concerns of tritium and activation products and on potential mechanisms for their release; these concerns include lithium fires, magnet accidents, plasma disruptions, and coolant-system failures. Safety-related data to be used in the activities will be generated by safety and fusion-technology experiments, by the materials-research program, and by such fusion facilities as TSTA, TFTR, the short-pulse ignition experiment, and the long-burn demonstration.

The primary activities in the environment subelement are: (1) to develop methodologies for analyzing and resolving waste-management issues, (2) to

prepare (or assist in preparation of) environmental reports for major fusion-research facilities, and (3) to analyze and develop strategies for utilization and recycling of fusion materials, especially those with near-term supply limitations. The primary generators of radioactive-waste data for this activity include TSTA, TFTR, the short-pulse ignition experiment, and the long-burn demonstration. The output of this activity will be used to prepare environmental reports for future facilities. Ongoing commercial-reactor design studies will be used to assess resource-utilization issues and the need for developing resource-utilization/recycling strategies.

The actual need for a fusion licensing system will not arise until after the beginning of the next century; however, the data requirements for such a system must be anticipated so that relevant data can be generated and collected by ongoing programs. Also, because of the impact that a licensing system can have on fusion economics and on the acceptability of the technology to utilities and the general public, a technically well-founded and streamlined system must be established. The activities in this subelement provide for safety-approval strategies for the major fusion experimental facilities and develop-

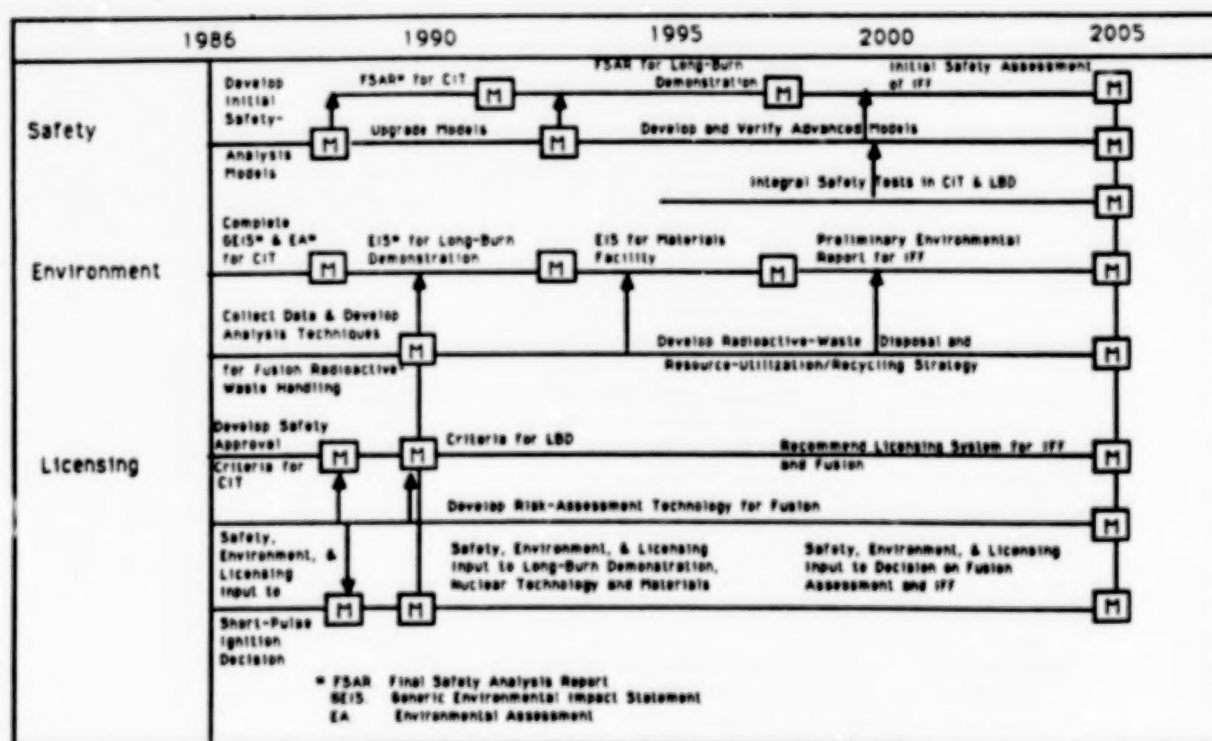


Fig. 7. Logic diagram for safety, environment, and licensing.



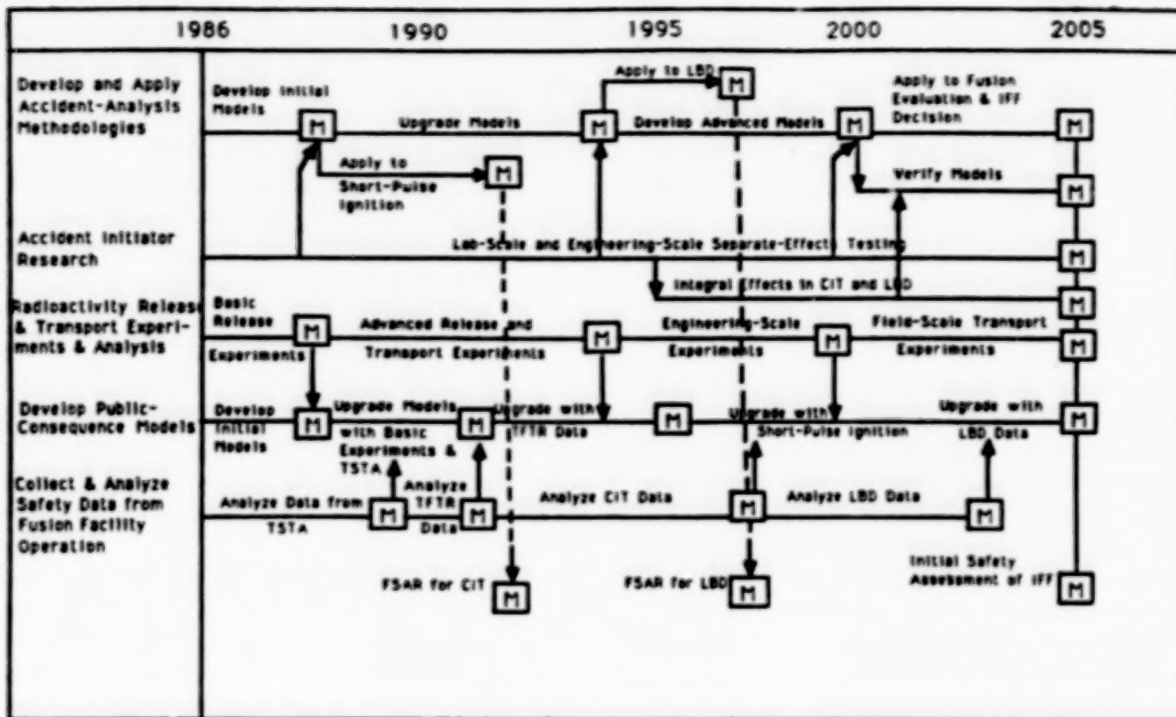


Fig. 8. Logic diagram for safety.

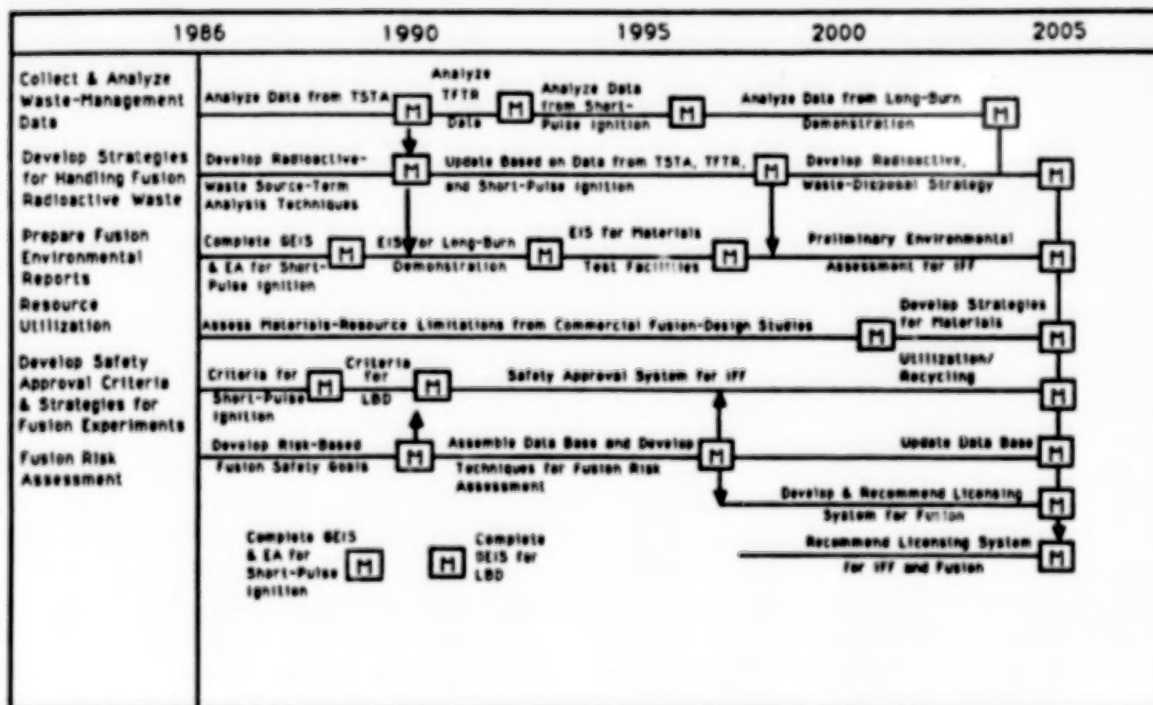


Fig. 9. Logic diagram for environment and licensing.



ment of the risk-assessment methodology that will form the basis for a fusion licensing system. This latter activity requires establishment of risk-based safety goals and collection of a fusion-relevant, failure-rate data base to allow the probabilities of various radioactivity-release scenarios to be calculated.

## REMOTE TECHNOLOGY

The primary purpose of the remote-technology program element is to develop the necessary equipment and procedures for design, operation, and maintenance of all future fusion devices, ultimately including commercial fusion plants. All fusion devices to date have been designed, operated, and maintained with the capability of full access by personnel and equipment when adjustments for operation, maintenance, or replacement of components have been necessary. Operation and maintenance in a highly activated environment have, until now, not been required. All future fusion devices will operate and require service in a highly activated environment. Providing for the operation and maintenance of such fusion devices will require substantial integration of remote-technology equipment and practices into the basic design of the device.

Substantial advances in remote technology can be anticipated in fields outside the fusion program. However, many aspects of the fusion program will be unique in the application of this technology. From the requirements unique to fusion will come the guidelines for the design of fusion-system components and the remote-technology equipment necessary to handle and maintain these components. At present, the fusion program relies on each major project to incorporate the remote technology needed in that project. To date, remote-technology needs have been modest, and it has not been necessary to develop a separate remote-technology program within the overall fusion program. Future, major fusion devices will require sufficient attention to remote-technology needs to warrant a base program, in addition to major efforts within large projects.

Planning the elements of the remote-technology base program, as well as defining the large project development needs, should be the first task performed in this program activity. Such planning should involve experts in the field of remote technology; few such experts are found within the fusion program. The

two dominant areas for which detailed planning is required are development of components and subsystems compatible with remote-technology applications and development of remote-technology equipment and procedures for future fusion needs.

The hardware associated with this program is embodied in a series of mock-up systems—one for the ignition experiment, one for the long-burn experiment, and one leading to the integrated fusion facility. An alternative approach would involve combining these systems into a dedicated Remote-Technology Development Facility that would support each future reactor project. The fundamental objectives of the remote-technology program are envisioned to be:

1. Establish the reliability of remote-technology equipment for use in the projected operating environment.
2. Modify existing equipment and develop new remote-technology equipment for anticipated operations and maintenance requirements; implement these on prototype reactor components. Existing equipment consists of teleoperated manipulator systems and transport systems, along with the support equipment to accomplish remote operations (i.e., viewing systems, cutting and welding equipment, and other end-effector tools). New developments will focus on robotic equipment that uses a greater degree of artificial intelligence.
3. Investigate the use of standardized interfaces on vacuum joints, coolant connections, electrical connections, and structural joints. Investigate interfaces with mechanical attachments and those that require cutting and welding.
4. Establish requirements for standard hardware and procedures.
5. Develop a remote-technology design and user manual that covers hardware, design practices, and applications principles.
6. Establish a data base for the mean time to repair (MTTR) based on prototype operations and experience from existing operating devices and equipment.
7. Establish a data base for mean time between failures (MTBF) of reactor equipment based on existing and ongoing experience with device operations.

## Issues, Objectives, and Attributes

The issues associated with the remote-technology program element are: (1) Fusion facilities will require design approaches and practices compatible

with the need to operate and maintain them remotely. Both the design and subsequent operation and maintenance must be performed in a cost-effective manner. (2) Fusion facilities will require complex remote-technology equipment, much of which is beyond the current state of the art.

The objectives and associated attributes for the issues are listed in Table IX.

### Program Logic

The logic diagram for this program element, shown as Fig. 10, is discussed.

### Develop, Issue, and Update Plan

This task includes the formulation of a comprehensive base program for remote technology within the fusion program. This program will define the context, tasks, coordination, schedule, and resources required to achieve remote-technology objectives in support of the overall program.

### Develop, Issue, and Update Guideline Document

This task includes the preparation and maintenance of a remote-technology handbook of design

Table IX. Objectives and Attributes for Remote-Technology Program Element

Objective	Attribute	Planning target
Maximize reactor availability	Minimization of MTBF and MTTR	Availability greater than 75%
Develop and use cost-effective remote maintenance equipment	Simple, modular subsystems and components; compatible remote-maintenance equipment	Equipment costs less than 20% of total capital costs
Minimize exposure of personnel to radiation	Application of remote-handling technology	Less than 25% of exposure permitted by federal regulations

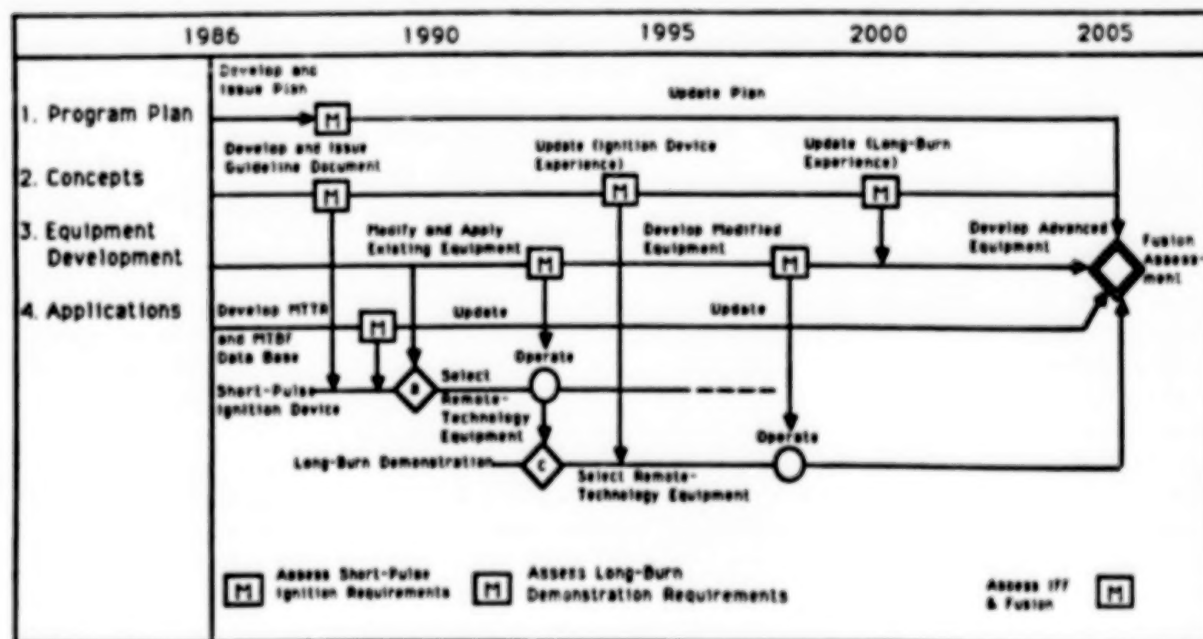


Fig. 10. Logic diagram for remote technology.

practices, principles, typical examples, equipment, and related information necessary for the cognizant design engineers to assure that all components and systems are designed to be compatible with the need for operations and maintenance by remote means.

Achieving high availability with remote technology will require the development and maintenance of a data base of relevant information essential to determination and minimization of the MTTR and the MTBF of equipment in fusion devices. This data base will be essential to the development of reliable equipment for fusion applications. Determination of the remote-technology equipment needed to maintain and operate future fusion devices is required. It includes specification of remote-technology practices essential to the effective use of such equipment. The equipment and practices for the design, installation, maintenance, and replacement of components and systems in fusion devices are included, as are all mock-up developments and associated test equipment. Incorporated into this effort are the necessary training and education of personnel essential to these efforts.

### ALTERNATIVE FUEL CYCLES

This program element covers the complete range of science and technology programs required for a non-DT fuel cycle and specifies the required programs that would not otherwise be carried out in support of DT fuel-cycle applications. Consequently, the following program subelements (see Fig. 2) have been chosen: (1) confinement systems and burning plasmas, (2) plasma technology, (3) nuclear technology and materials, (4) systems design and analysis.

#### Issues, Objectives, and Attributes

The development of an alternative (nontritium) fuel cycle represents a potentially attractive long-range goal for fusion. A base research program and continued assessment of nontritium fuel cycles will allow directions in DT fusion development to be identified that are consistent with potential evolution into an attractive alternative fusion fuel. Operation of fusion systems with a fuel cycle other than DT could significantly reduce certain constraints on reactor design by eliminating the requirement for a tritium-breeding blanket. Eliminating this requirement could allow a much wider range of structural and thermal hydraulic designs, resulting in blankets with

higher thermal efficiency. Improved overall designs for reactor assembly and repair may be possible, and greater reliability may also be attainable. However, use of a nontritium fuel cycle means that substantially improved values of beta and density-confinement-time product are necessary relative to those required for DT operation. In addition, devices of larger size and/or stronger magnetic fields may be required in order to use such alternative fuels.

The issues associated with the alternative-fuels program element are: (1) The plasma-confinement conditions required for the alternative fuel cycles must be achievable. (2) The technologies unique to alternative-fuel-cycle applications must be developed. (3) The concepts for alternative fuel cycles must meet the systems requirements for commercial applications.

The objectives and associated attributes for the resolution of these issues are listed in Table X.

#### Program Logic

The logic diagram for this program element is shown in Fig. 11; the program logic is discussed below.

#### *Confinement Systems and Burning Plasmas*

This task involves theoretical and experimental physics activities to establish the feasibility of concepts based on fuel cycles other than deuterium and tritium. There are two basic alternative cycles: deuterium-based (D-based) and proton-based (*p*-based) cycles. The present plan is directed mainly at D-based cycles, because these cycles indicate high-energy gain can be achieved with ambitious, but possible, plasma parameters. The possibility of igniting *p*-based cycles, however, remains questionable. Two aspects of D-based cycles should be stressed:  $DHe^3$  is an attractive cycle, offering a significant reduction in neutron flux with only a modest increase in ignition requirements. Other D-based cycles could lead to attractive hybrid (fusion-fission) and synfuel systems.

A key limitation of the  $DHe^3$  cycle is the issue of where to obtain the  $He^3$ . An important recent development is the recognition that mining the lunar surface could provide a plentiful, economic supply of  $He^3$ . This might make alternative fuels a competitive route to fusion power.

Another possibility is DD/DT operation, where the required tritium-breeding ratio is less than one.



Table X. Objectives and Attributes for Alternative Fuels Program Element

Objectives	Attributes
Minimize production and handling of tritium	Cost of tritium-handling subsystem, expressed as percent of total plant cost
Minimize production of neutrons	Fraction of total fusion energy carried by neutrons, expressed as percent
Maximize potential for nonthermal energy conversion	Overall plant efficiency, in percent
Maximize capability to achieve the higher beta and confinement times necessary for alternative-fuel systems	Predictive capability of plasma theory to verify experiment

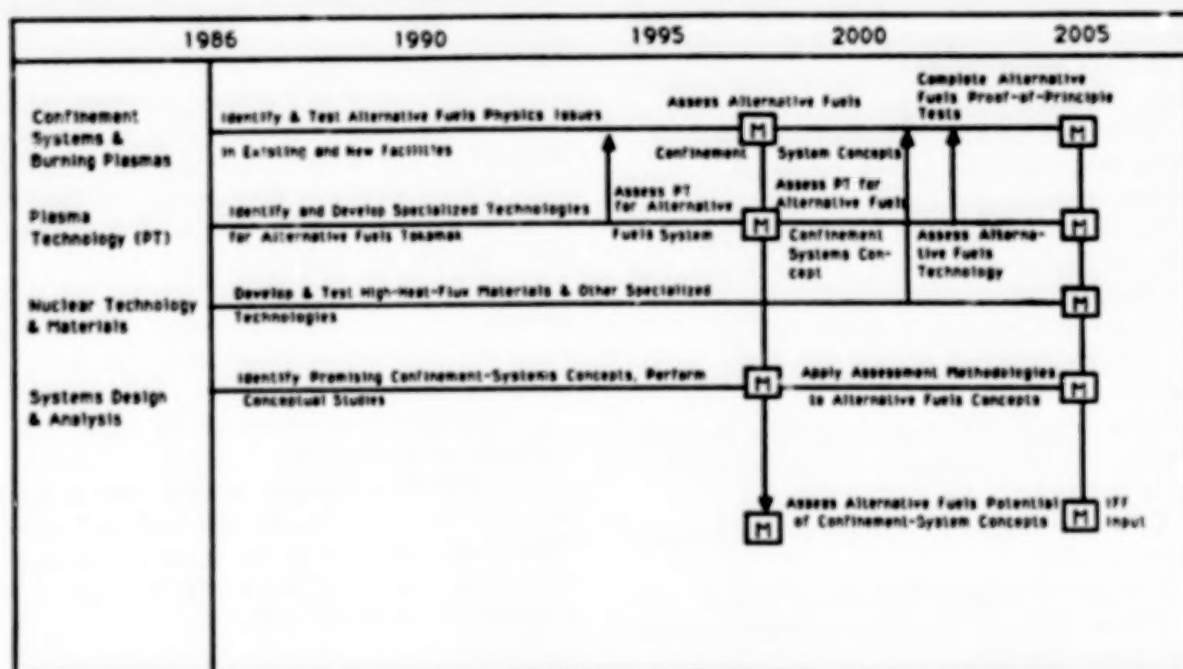


Fig. 11. Logic diagram for alternative fuels.

Breeding requirements are reduced, relative to those for DT operation, but the plasma-physics requirements are not as severe as those for DD operation. The physics requirements for operation of hybrid fusion-fission reactors with DD and DD/DT fuel cycles could be substantially less demanding than for the operation of pure fusion DD reactors.

Issues associated with confinement systems and burning plasmas are:

1. Requirement for very high beta places emphasis on alternative confinement concepts with high beta.

2. Requirement for high-temperature plasmas would emphasize possible extension of DT ignition experiment(s) to stress heating and burn dynamics at higher temperature.

3. Confinement concepts using alternative, non-tritium fuels require high-beta and high-temperature plasma; such concepts must be developed.

4. The potential for direct energy conversion is a desired feature that must be developed.

5. High-temperature, high-density operation leads to increased importance of and sensitivity to plasma-wall interactions, with emphasis needed on

## Commercial Objectives, Technology Transfer, and Systems Analysis

understanding impurity-generation mechanisms, transport, and control.

6. Fusion cross-section data for alternative fuels must be obtained.

### Plasma Technology

This area involves the development of technologies unique to handling the plasmas associated with nontritium fuels. Alternative-fuel fusion involves two key characteristics: (1) a high beta or high field to compensate for the relatively low-plasma power density and (2) a high-plasma temperature to achieve ignition. Corresponding engineering constraints require the ability to handle a relatively high first-wall heat load and development of methods to capitalize on the large charged-particle fusion yield (e.g., direct energy conversion). Issues include:

1. Efficient methods are needed to achieve higher ignition temperatures (e.g., bootstrap heating in combination with normal methods).
2. Heating methods are needed that operate at higher temperatures (e.g., negative ion beams and wave heating).
3. Fueling technology is needed for  $\text{He}^3$ .
4. Methods of impurity control must be developed.
5. A reliable fuel source must be established, especially for  $\text{He}^3$  (evaluate lunar mining, satellite approaches, etc.).
6. Advanced and direct energy-conversion methods are needed.
7. High-field magnet technology is needed.
8. Plasma-control systems are needed to prevent rapid plasma quenches.

### Nuclear Technology and Materials

This element consists of development activities associated with the nuclear technologies and materials required for alternative-fuel fusion systems. One objective of alternative fuel cycles is to minimize the production of neutrons, so the nuclear technology requirement for alternative fuel-cycle systems is expected to be adequately covered by R&D for DT systems, and no special requirements are projected. Materials needs are expected to be mostly in the area of handling high heat flux.

### Systems Design and Analysis

This area consists of studies of alternative fuel systems. Studies are required to:

1. Evaluate the potential of alternative fuels on a basis consistent with DT-based studies.
2. Establish attractive systems-integrated approaches to high-beta value, improved confinement concepts, direct energy conversion, and unique blanket designs.
3. Identify needs and build on the emerging DT data base.
4. Develop test-facility designs and commercial-design concepts.
5. Identify attractive alternative applications that offer unique advantages (e.g., hybrid and synfuels plants).

The key activities are:

1. Select the most promising high-beta confinement concepts for burning alternative fuels. This selection will require studies of available theoretical and experimental data for such concepts as high-field tokamaks, compact tori, reversed-field configurations, tandem mirrors, etc.
2. Identify possible reactivity-enhancement approaches. Enhancement is not essential for D-based fuels, but if  $p$ -based cycles are to be considered, this is mandatory.
3. Identify cross-section needs. Again, this is essential for  $p$ -based cycles.
4. Identify experiments to study ways to handle the high heat flux on the first wall and identify technology developments (e.g., direct energy conversion) that would provide a high leverage in the utilization of alternative fuels.

### ACKNOWLEDGMENTS

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**SYNERGISM OF He-3 ACQUISITION WITH LUNAR BASE EVOLUTION\***

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## 1.0 INTRODUCTION

The 21st century will see great advances in the exploration of space. Beginning with a space station in low Earth orbit and moving toward the settlement of extraterrestrial planets, the exploration and development of space will broaden mankind's horizons. The establishment of a permanently manned Lunar Base would create an excellent stepping stone to future space exploration missions. These advanced missions may support development of large inexpensive power on Earth through the evolution of a very attractive fusion reaction involving deuterium and an isotope of helium, He-3. The advantages of this reaction include: reduced radioactivity due to a reduction of neutrons emitted; improved safety over other fusion reactions and all fission reactions; increased efficiency; and lower electricity costs. Because terrestrial quantities of He-3 would not support a fusion energy economy, researchers are looking to the Moon as a source of He-3 (Wittenberg, 1986). The Moon has been shown to contain approximately 1,000,000 metric tons of He-3 from solar wind bombardment over the past 4 billion years.

This paper will show how acquisition of He-3 affects Lunar Base development and operation. A four-phase evolutionary Lunar Base scenario is summarized with initial equipment mass and resupply requirements. Requirements for various He-3 mining operations are shown and available by-products are identified. Impacts of mining He-3 on Lunar Base development include increases in equipment masses to be delivered to the lunar surface and a reduction of Lunar Base resupply based on availability of He-3 acquisition by-products. The paper concludes that the acquisition of this valuable fusion fuel element greatly enhances the commercial potential of a Lunar Base.

## 2.0 EVOLUTIONARY LUNAR BASE SCENARIOS

To determine requirements for the establishment of a Lunar Base, various phases of Lunar Base development must be identified. Subsystems required for base operation must be defined. Mass, power, and resupply requirements for these operations must be determined to address overall transportation requirements and cost of operations. From previous Lunar Base concepts and current technology projections, evolutionary Lunar Base scenarios are summarized from previous studies to assess impacts of integrating Lunar He-3 mining into a Lunar Base.

The evolutionary Lunar Base scenarios consist of four phases: (1) a man-tended science base; (2) a manned science and technology base; (3) a manned science and manufacturing base; and (4) a manned science, manufacturing, and export base. Each phase builds on an evolutionary operating capability. The bases's manned capability grows from 4-6 crew members on the man-tended base to supporting 15-20 permanently manned crew members over a period of 23 years.

The initial Lunar Base scenario can support 4 to 6 crew for a 10 day mission. Missions performed on this Lunar Base would be mainly science oriented. Science missions include geology, life sciences/medicine, astronomy, technology testing, and study of energy systems. No provisions for processing lunar regolith for rocket propellant or other resources are provided in this stage of Lunar Base development.

The next stage of Lunar Base development would allow for continuous occupancy of the base by 4 to 6 crew. General science operations would be expanded to include specific studies of geology, life

sciences/medicine, and technology testing. Chemical processing of lunar regolith would involve hydrogen reduction of ilmenite for lunar oxygen. A small scale mining operation would be initiated to supply the base with the needed regolith for lunar oxygen production (6.6 MT lunar regolith per 1 MT lunar oxygen).

In the third stage of Lunar Base development, continuous support for 10 crew is provided. Carbothermal reduction is added to hydrogen reduction to expand regolith processing capability allowing for production of lunar resources beyond lunar oxygen (29.2 MT lunar regolith per 1 MT lunar oxygen + 1 MT lunar silane + 0.4 MT lunar silicon for carbothermal reduction). The additional lunar resources produced can be used for fabrication of structures, solar panels and various other products useful to the base. Provisions to allow manufacturing of these type of products must be provided in this stage of Lunar Base development. Mining operations are expanded to provide the needed additional lunar regolith for manufacturing and production. This expanded mining scenario may include the beginnings of a conveyor network to enable acquisition of larger quantities of lunar regolith.

In the fourth stage of the evolutionary Lunar Base scenarios the base is capable of supporting 15 to 20 crew continuously. To increase the self sufficiency of the base, a process similar to HF acid leach would be added to the chemical processing facility to obtain lunar aluminum and provide the potential to obtain other elemental resources for structures (8.7 MT lunar regolith per 1.0 MT oxygen + 0.6 MT aluminum). Magma electrolysis is added to obtain lunar iron for structures (132.5 MT lunar regolith per 1.0 MT oxygen + 0.8 MT iron). Shiftable conveyors would be added to the mining scenario to provide the additional regolith needed for manufacturing and production. Shiftable and permanent conveyors could be added as the demand for lunar regolith increases.

## 2.1 Lunar Base Subsystems

Lunar Base subsystems required are determined from the three major operations to be performed by a Lunar Base which include science, manufacturing and production, and infrastructure/support. These operations expand differently as a Lunar Base scenario evolves. Table 2-1 summarizes mass delivery requirements for each subsystem of the evolutionary Lunar Base scenario.

TABLE 2-1. SUBSYSTEM MASS REQUIREMENTS FOR THE EVOLUTIONARY LUNAR BASE SCENARIO

LUNAR BASE SUBSYSTEM	PHASE OF EVOLUTIONARY LUNAR BASE SCENARIO			
	1	2	3	4
SCIENCE	25	125	175	200
MANUFACTURING & PRODUCTION	--	12	431	1115
INFRASTRUCTURE	28	58	133	590

ALL MASSES ARE IN METRIC TONS

Science missions are an important part of any Lunar Base scenario. These missions are needed to provide the information on Lunar geology, life sciences/medicine, astronomy, technology testing, and the study of energy systems. The science system for these Lunar Base scenarios was modeled from the current space station laboratory modules (JSC 30255). In the early stages of Lunar Base development, one module might support small scale experiments for many of these science missions. As the base grows, modules dedicated to a specific types of science missions may be added.

The manufacturing and production system is the main contributor to self-sufficiency capability. While emphasis on this system is low in the early stages of base development, it has the highest priority in an evolved Lunar Base configuration. Manufacturing and production operations include chemical processing for lunar resources, fabrication of hardware or structures from lunar and terrestrial materials, and mining operations for acquisition of lunar regolith. Chemical processing may only involve extraction of oxygen from lunar regolith in the early stages of base development. As the base grows, processing for additional lunar resources will be required. Fabrication of hardware or structures will only be required in fairly evolved Lunar Base scenarios, because larger scale structures and hardware are required before the additional mining and processing operations become cost effective. Mining operations for lunar He-3 include lunar surface transport vehicles, permanent and shiftable conveyors, and beneficiation of lunar ores.

Infrastructure and support includes habitats, launch/landing facilities (includes a mass driver system), maintenance facilities, and power. The infrastructure can be thought of as a base on which all lunar operations are built upon. The infrastructure must provide all resources (mainly consumable, power, thermal, and crew resources) to support science and manufacturing operations. The power plant within the infrastructure can be thought of as LP&L (Lunar Power and Light) and must provide sufficient power for all community needs.

The evolutionary Lunar Base scenarios are capable of utilizing lunar resources after initial operating capability is reached for the second phase of development. Initially, production will be centered on acquisition of lunar oxygen. As the base evolves, structural materials would be needed to ease expansion requirements by using lunar-derived materials. Figure 2-1 shows the production capability of each phase of base development. It is important to note that science system outputs may not be of a product nature, but enhance the knowledge base of Earth and lunar inhabitants.



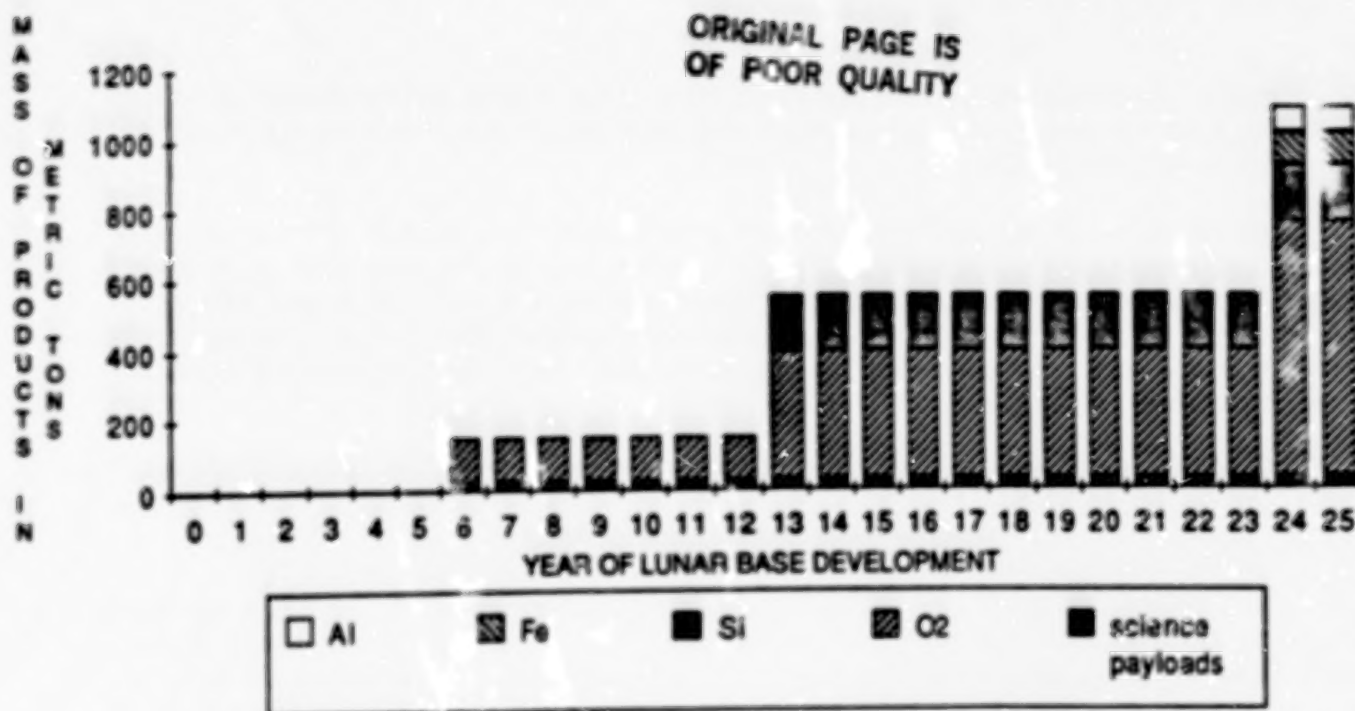


FIGURE 2-1. ANNUAL LUNAR BASE PRODUCTION CAPABILITIES

## 2.2 LUNAR BASE RESUPPLY

Resupply mass requirements include mass for hardware refurbishment, as well as for consumable replenishment. Resupply requirements have been divided into the three major Lunar Base subsystems. Figure 2-2 summarizes operational resupply requirements for each Lunar Base subsystem and for each phase of base development.

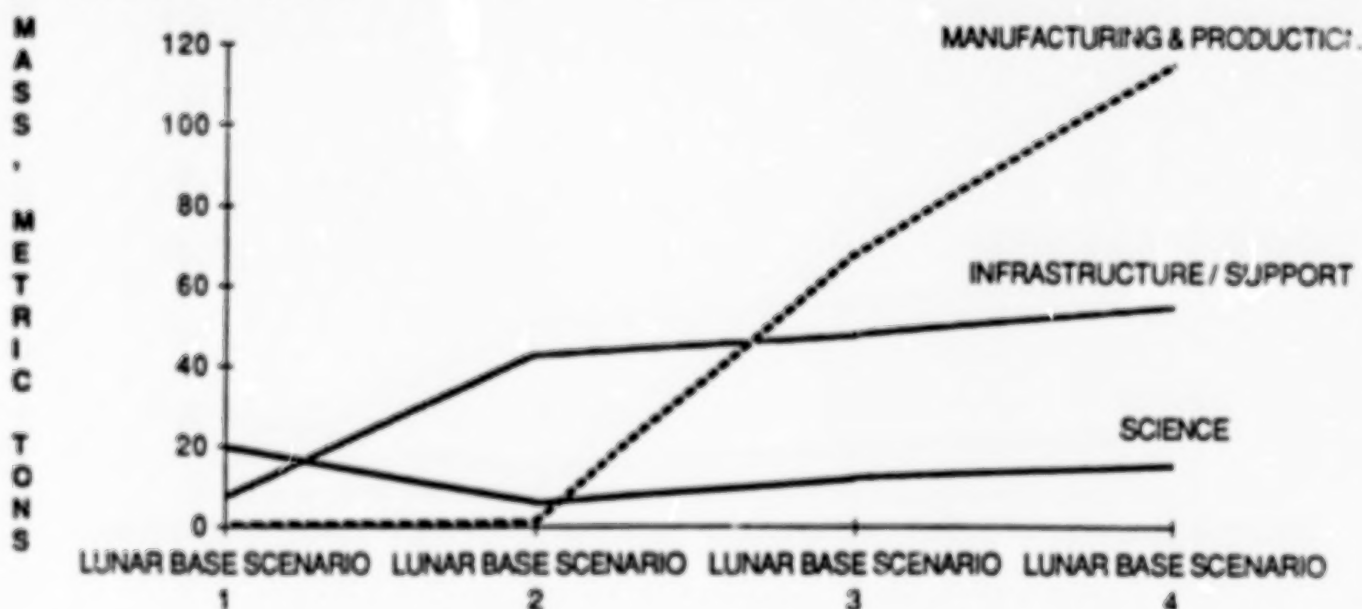


FIGURE 2-2. LUNAR BASE ANNUAL RESUPPLY MASSES

Resupply for the science system is partly comprised of hardware for refurbishment of laboratory modules but is mainly made up of science payloads that are delivered from Earth to conduct scientific experiments on the Lunar surface.

Over 75% of the resupply in the manufacturing and production system is to replenish unrecycled reactants used in processing of Lunar regolith. Some hardware resupply is required to refurbish failed mining system components. Required resupply for unrecycled reactants/consumables and hardware refurbishment is not assumed to be from a Lunar source, although many of the consumables required for regolith processing may be made available from extraction of He-3 and other solar wind gases (will be covered in section 4.1 of this paper).

The major contributor to resupply requirements for the infrastructure\support system originates from life support consumables. Water, the largest consumable in the life support system, may be available in sufficient quantities with the addition of a He-3 mining operation (see section 4.1 of this paper).

A major advantage of He-3 acquisition for a Lunar Base is to make quantities of many consumables that would need to be delivered from Earth available from Lunar resources. To identify these benefits, specific quantities of consumable resources required by a Lunar Base must be identified. Consumable resource requirements can be obtained from analysis of resupply requirements for the manufacturing and production system and the infrastructure\support system. Resupply breakdowns for these Lunar Base systems can be found in Table 2-2.

**TABLE 2-2. BREAKDOWN OF CONSUMABLE RESUPPLY**

LUNAR BASE SUBSYSTEM	PHASE OF EVOLUTIONARY LUNAR BASE SCENARIO			
	1	2	3	4
PROCESS CONSUMABLES				
H <sub>2</sub>	--	186	372	558
CH <sub>4</sub>	--	--	60,000	60,000
HF	--	--	--	33,000
LIFE SUPPORT CONSUMABLES				
H <sub>2</sub> O	3,350	1,834	3,668	4,280
O <sub>2</sub>	450	247	493	570
N <sub>2</sub>	250	137	275	323

ALL MASSES ARE IN kg/yr

These resupply requirements determine transportation requirements for normal Lunar Base operation without expansion considerations. He-3 acquisition may increase hardware mass supply requirements but can relieve the requirement for consumables to be transported to the lunar surface from Earth.

### 3.0 LUNAR HE-3

Lunar sources of He-3 were first discovered in 1970 by R.O. Pepin (11th Lunar Science Conference). In 1986, a study conducted by scientists at the University of Wisconsin (Wittenberg, 1986) estimated the potential He-3 reserves on the Moon to be one million metric tons. Terrestrial sources of this resource are from the decay of tritium and are estimated at a few hundred kilograms per year. Terrestrial quantities of He-3 are not sufficient for a large scale fusion power industry which would require up to 10 metric tons He-3 per year (Kulcinski, 1988). This section defines requirements of a lunar He-3 mining operation and potential by-products that could be acquired with minimal additional resource requirements.

#### 3.1 Energy Value of He-3

The advantages of fusion energy utilizing He-3 are many. These advantages have been noted by the Fusion Technology Institute and the Nuclear Engineering and Engineering Physics Department of the University of Wisconsin at the Fifth Symposium on Space Nuclear Power Systems (11-14 January 1988). Approximately 600,000 GJ of energy, or 19 MW<sub>th</sub>, is released upon burning 1 kg of He-3 with deuterium. Thermal to electrical conversion efficiency for the D-He3 fusion reaction is high, approximately 70%. This would yield an electrical energy content of 11.4 MW<sub>e</sub> per kg of He-3.

Lunar He-3 production levels are estimated to start at approximately 10 kg per year and would increase to several thousands of kg's annually within 30-40 years of the start of lunar He-3 mining. The impacts are very significant on North America energy production and may prove even more significant on future energy requirements in space.

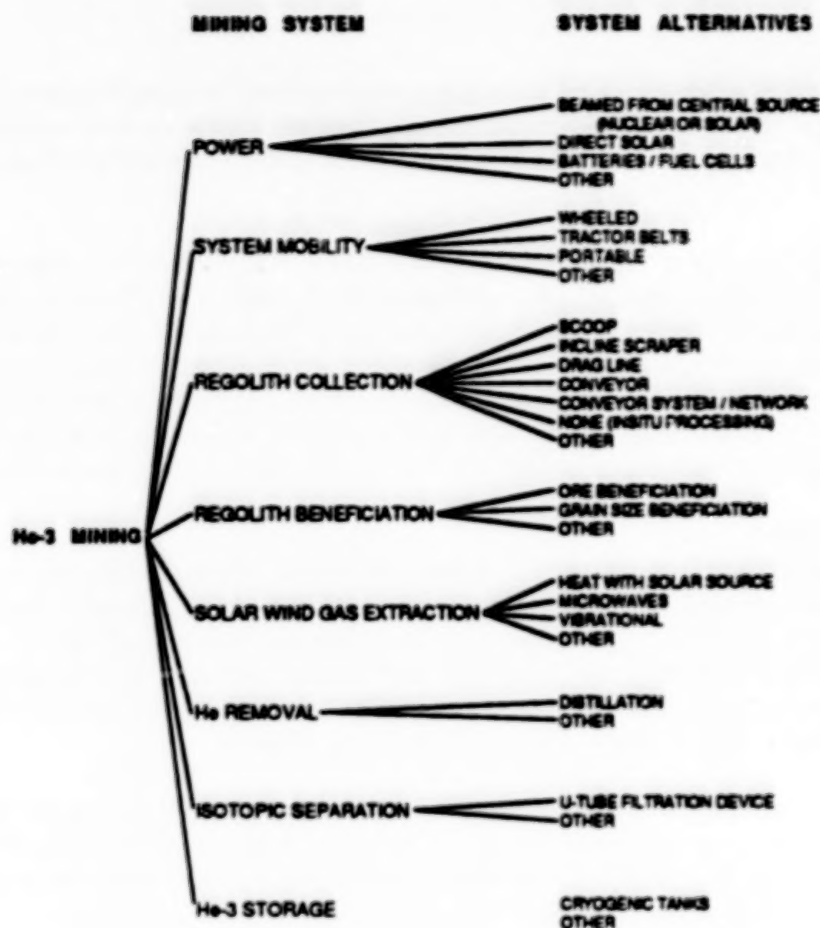
#### 3.2 He-3 Concentrations in Lunar Mare Regolith

Lunar He-3 sources originate from solar winds that have bombarded the lunar surface over the past 4 billion years. Analyses of lunar samples returned in the days of the Apollo missions show helium concentrations in lunar mare regolith of 30 ppm. The concentration of He-3 in helium has been estimated to be 300 ppm. Thus,  $1.11 \times 10^8$  kg of unbeneficiated lunar mare regolith would contain 1 kg of He-3. Since mare samples show a high degree of homogeneity, it is assumed that these concentrations are consistent to at least a 3 m depth. Thus, an area of 25,370 m<sup>2</sup> would contain 1 kg of He-3.

Because the heat capacity of lunar regolith is so low (0.784 J/g K), regolith should be beneficiated as much as possible to reduce the quantities of regolith that must be heated. Beneficiation to remove larger grains can yield reductions of Lunar regolith that must be heated by almost 50% with acquisition of 70-80% of total He-3 available.

#### 3.3 Requirements for He-3 Acquisition

He-3 and other solar wind gas constituents can be removed from lunar regolith through heating. Regolith is collected, beneficiated to a specific grain size fraction, and heated. After heating to approximately 700 C, many of the solar wind gases are evolved. Further processing of these gases would remove He-3 from the solar wind gas mixture. Alternative technologies for the various systems required for lunar He-3 acquisition are included in Figure 3.-1.



**FIGURE 3-1. HE3 MINING SYSTEM ALTERNATIVES**

Two scenarios have been conceptualized for the mining of Lunar He-3. The first scenario is a mobile miner that would collect the regolith, beneficiate, and evolve the solar wind gases. The gases would then be collected and stored in gas storage vessels which would be transported to a central facility for further processing. The second scenario is a centralized mining concept where sufficient quantities of bulk lunar regolith would be collected, placed on a conveyor system which would transport the regolith to a central facility for beneficiation, solar wind gas removal, and separation of solar wind gas constituents. A summary of mass and power requirements for each of the He-3 mining scenarios is provided in Tables 3-1 and 3-2 respectively.

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**TABLE 3-1. MASS SUMMARY FOR HE3 MINING SCENARIOS**

ALL MASSES ARE IN METRIC TONS

<b>LUNAR HE-3 MINING CONCEPT</b>	<b>REGOLITH COLLECTION</b>	<b>REGOLITH BENEFICIATION</b>	<b>SOLAR WIND GAS EXTRACTION</b>	<b>SELECTIVE CONDENSATION</b>	<b>ADDITIONAL</b>
<b>MOBILE MINER - 1000 kg He3/yr</b>					
BUCKET WHEEL	152				
INTERNAL REGOLITH TRANSPORT	49				
ELECTROSTATIC BENEFICIATOR		20			
THERMAL POWER FROM DIRECT SOLAR			242		
SELECTIVE CONDENSATION UNIT				180	
GAS STORAGE VESSELS					67
GAS STORAGE VESSEL TRANSPORT VEHICLE					18
MINER MOBILITY SYSTEM & BODY					83
<b>TOTALS</b>	<b>201</b>	<b>20</b>	<b>242</b>	<b>180</b>	<b>168</b>
<b>CENTRALIZED CONCEPT - 1000 kg He-3/yr</b>					
BUCKET WHEEL EXCAVATORS	200				
CONVEYOR SYSTEM	645				
ELECTROSTATIC BENEFICIATOR		20			
NUCLEAR THERMAL POWER			10		
SELECTIVE CONDENSATION UNIT				180	
<b>TOTALS</b>	<b>845</b>	<b>20</b>	<b>10</b>	<b>180</b>	

**TOTAL MASS FOR MOBILE MINER = 811 metric tons**

**TOTAL MASS FOR CENTRALIZED CONCEPT = 1,055 metric tons**



**TABLE 3-2. POWER SUMMARY FOR HE3 MINING SCENARIOS**

ALL POWER VALUES ARE IN KILOWATTS

<b>LUNAR HE-3 MINING CONCEPT</b>	<b>REGOLITH COLLECTION</b>	<b>REGOLITH BENEFICIATION</b>	<b>SOLAR WIND GAS EXTRACTION</b>	<b>SELECTIVE CONDENSATION</b>	<b>ADDITIONAL</b>
<b>MOBILE MINER - 1000 kg He3/yr</b>					
BUCKET WHEEL	910				
INTERNAL REGOLITH TRANSPORT	152				
ELECTROSTATIC BENEFICIATOR		150			
THERMAL POWER FROM DIRECT SOLAR			4,848		
SELECTIVE CONDENSATION UNIT				5,450	
GAS STORAGE VESSELS					-
GAS STORAGE VESSEL TRANSPORT VEHICLE					242
MINER MOBILITY SYSTEM & BODY					1,110
<b>TOTALS</b>	<b>1,062</b>	<b>150</b>	<b>4,848</b>	<b>5,450</b>	<b>1,352</b>
<b>CENTRALIZED CONCEPT - 1000 kg He-3/yr</b>					
BUCKET WHEEL EXCAVATORS	870				
CONVEYOR SYSTEM	6,105				
ELECTROSTATIC BENEFICIATOR		150			
NUCLEAR THERMAL POWER			5,675		
SELECTIVE CONDENSATION UNIT				5,450	
<b>TOTALS</b>	<b>6,975</b>	<b>150</b>	<b>5,675</b>	<b>5,450</b>	

**TOTAL POWER FOR MOBILE MINER = 12,862 kW**

**TOTAL POWER FOR CENTRALIZED CONCEPT = 18,250 kW**

Both He-3 mining scenarios are based on an annual He-3 production rate of 1 metric ton. Thermal energy requirements for solar wind gas evolution are based on the heat capacity of lunar regolith and assume 85% heat recovery. The major difference in the solar wind gas extraction subsystem designs among the alternatives is the source of thermal energy. The mobile miner uses a solar collector/concentrator of smaller thermal output while the centralized system utilizes the high thermal energy output of a nuclear SP-100 reactor. It should be noted that the requirements for the centralized mining concept are impacted by movement of the regolith collection subsystem from a mined area to a different unmined area. Surface preparation requirements for this transportation are not included in either concept. Also, storage requirements for resources obtained following selective condensation are not included in either mining concept.

### 3.4 Mobile vs. Centralized Mining Concepts

To evaluate and compare each mining concept, advantages and disadvantages of each concept must be identified. The advantages and disadvantages for each mining concept can be found in Tables 3-3 and 3-4.

TABLE 3-3. ADVANTAGES/DISADVANTAGES OF THE MOBILE MINER

ADVANTAGES	DISADVANTAGES
MINIMAL ALTERATION OF LUNAR SURFACE	PREDICTED HE3 DEMANDS WOULD REQUIRE OVER 100 MOBILE MINER SYSTEMS BY THE YEAR 2050
HIGH DEGREE OF AUTOMATION POSSIBLE	OPERATION ONLY DURING THE LUNAR NIGHT REDUCES POTENTIAL HE3 PRODUCTION RATES
NO TEAR DOWN / SET UP REQUIREMENTS FOR MINING DIFFERENT AREAS FAR FROM CENTRAL BASE	BECAUSE MAINTENANCE OF SEVERAL MOBILE MINERS, SOME MANY KM FROM THE CENTRAL BASE, IS VERY RESOURCE INTENSIVE, SYSTEMS WITHIN THE MINER MUST HAVE MINIMAL COMPLEXITY
MULTIPLE MINERS CAN COVER A VERY LARGE SURFACE AREA	
OPERATES FAIRLY INDEPENDENTLY OF OTHER LUNAR BASE OPERATIONS	
HAS A LOWER MASS PER KG HE3 OBTAINED THAN CENTRALIZED CONCEPT	

**TABLE 3-4. ADVANTAGES/DISADVANTAGES OF THE CENTRALIZED MINING CONCEPT**

<b>ADVANTAGES</b>	<b>DISADVANTAGES</b>
<p>MUCH OF THE HARDWARE REQUIRED COULD BE UTILIZED BY A LUNAR BASE FOR OXYGEN PRODUCTION AND OTHER MINING ACTIVITIES</p> <p>OPERATION DURING THE LUNAR DAY AND NIGHT</p> <p>SINCE MANY OF THE GAS REMOVAL / COLLECTION SYSTEMS ARE CENTRALLY LOCATED, SERVICING / MAINTENANCE IS LESS COSTLY THAN IN MOBILE SYSTEMS AND MAY BE DESIGNED WITH HIGHER LEVELS OF COMPLEXITY USING SOA TECHNOLOGIES</p>	<p>HAS A HIGHER MASS PER KG HE3 THAN MOBILE</p> <p>MOVING THE MINING OPERATION TO ANOTHER LOCATION WOULD BE VERY RESOURCEINTENSIVE</p> <p>BECAUSE MORE SYSTEMS ARE LOCATED IN THE CENTRAL FACILITY THAN WITH THE MOBILE MINER, THERE WILL BE MORE SIGNIFICANT IMPACTS ON THE LUNAR BASE INFRASTRUCTURE</p> <p>SINCE LARGE QUANTITIES OF REGOLITH NEED TO BE DELIVERED TO THE CENTRAL FACILITY FOR PROCESSING, PROBLEMS OF ACCUMULATION OF PROCESSED REGOLITH STOCKPILES MAY ARISE</p>

When studying the advantages and disadvantages of each concept, many tradeoffs become apparent. Because the solar wind gas extraction system in the centralized concept is in one central location, a nuclear reactor could be used to deliver required thermal power enabling gas extraction to occur in the Lunar day and night. Implementing the use of nuclear reactors on the mobile miner would create many maintenance and safety problems because the systems would be more difficult to closely monitor. An advantage of the mobile miner is that large areas may be easily mined at any distance from the central base. As He-3 production requirements increase and as He-3 is removed from regolith nearby the central base, mining operations must extend distances far from the central base. Because movement of excavation systems in the centralized concept would be very costly, the mobile miner has a greater potential to meet long-range He-3 production requirements.

A major advantage of the centralized mining concept over the mobile miner is commonality of hardware. The excavation and conveyor systems required by the centralized concept can be used to collect regolith for oxygen and other Lunar resource processing schemes. This would reduce the mass delivery requirements for the manufacturing and production Lunar Base system. The excavation systems of the Lunar Base and the centralized He-3 mining concept are identical. The entire conveyor system mass of the fourth phase of the evolutionary Lunar Base scenarios could be provided by the centralized concept also. Considerations of shared hardware reduces mass delivery requirements for the manufacturing and production system by 8% for the centralized He-3 mining concept.

#### **4.0 IMPACTS OF HE-3 ACQUISITION ON LUNAR BASE DEVELOPMENT**

To determine the impacts of mining lunar He-3, we must first identify the advantages and disadvantages of each mining concept. We must then consider how the implementation of each mining concept affects the mass delivery requirements of the Lunar Base. The delivery of mining hardware generally increases mass delivery requirements, but the use of by-products made available by such mining would reduce the mass delivery requirements and increase the efficiency of the hydrogen/oxygen Earth-

Moon transportation systems. The value of He-3 and the significant quantities of the by-products available that enhance the commercialization potential of the Lunar Base.

#### 4.1 Available By-products

Many of the other constituents of the solar wind gas mixture are valuable to Lunar Base operations and are obtained with minimal additional resource requirements - thru "synergistic" processing. Table 4-1 lists these available by-products and the quantities available upon heating Lunar regolith to 700 C.

**TABLE 4-1. GAS RELEASE PREDICTED FROM HEATING  
MARE REGOLITH TO 700 C**

CONCENTRATION, ppm (g/metric tonne)								
OPERATION	Regolith (tonnes)	He-3	He-4	H <sub>2</sub>	Carbon			Nitrogen
Surface Mining	1	9x10 <sup>-3</sup>   90%	30   90%	50-80   90%	142-228   90%			102-153   90%
Beneficiate < 80 μm	0.46	8.1x10 <sup>-3</sup>	27	50	166			115
Heat to 700°C	0.45 (beneficiated)	86% 7x10 <sup>-3</sup>	81% 22	85% 43 (H <sub>2</sub> ) 23 (H <sub>2</sub> O)	3.8% 13.8 (CO)	2% 12 (CO <sub>2</sub> )	8% 11 (CH <sub>4</sub> )	3.2% 4
Per 1 kg He-3	1.37x10 <sup>5</sup> (mined) minor gases: neon 0.3 tonnes; argon 0.2 tonnes	1 kg	3.1 tonnes	6.1 tonnes (H <sub>2</sub> ) 3.3 tonnes (H <sub>2</sub> O)	1.9 tonnes (CO) 1.7 tonnes (CO <sub>2</sub> ) 1.6 tonnes (CH <sub>4</sub> )			0.5 tonnes
Per Tonne Regolith into Heater	1 (beneficiated) minor gases: neon 4.8 g; argon 3.2 g	0.016 g	49 g	96 g (H <sub>2</sub> ) 78 g (H <sub>2</sub> O)	30 g (CO) 27 g (CO <sub>2</sub> ) 24 g (CH <sub>4</sub> )			9 g

#### 4.2 Reduction in Lunar Base Logistics

Figure 4-1 shows the overall mass delivery requirement for the evolutionary Lunar Base scenarios without He-3 mining.

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**FIGURE 4-1. OVERALL MASS DELIVERY REQUIREMENTS FOR THE EVOLUTIONARY LUNAR BASE SCENARIOS**

The impacts of each He-3 mining concept on a Lunar Base can be determined by comparing the mass delivery requirements of the Lunar Base without He-3 mining to a Lunar Base implementing a He-3 acquisition scenario.

Table 2-1 showed resupply requirements for the manufacturing and production system and the infrastructure. The consumables that require resupply may be provided from by-products of He-3 acquisition. Table 4-2 shows the Lunar Base consumable requirements and the quantities available as by-products of He-3 mining scenarios.

**TABLE 4-2. ADDITIONAL RESOURCES AVAILABLE FROM HE3 ACQUISITION FOR LUNAR BASE SUPPORT**

RESOURCE	APPLICATION TO LUNAR BASE	ESTIMATED REQUIREMENT FOR 15-20 PERSON BASE * (kg/yr)	KG/KG HE3
H2O	LIFE SUPPORT CONSUMABLE	4,280	3,300
O2	LIFE SUPPORT CONSUMABLE	570	2,322 <sup>(a)</sup>
N2	LIFE SUPPORT CONSUMABLE	323	500
H2	LUNAR RESOURCE PROCESS CONSUMABLE	558	6,100
CH4	LUNAR RESOURCE PROCESS CONSUMABLE	60,000	1,600

\* LUNAR BASE INCLUDES FULL SCALE MINING OPERATIONS, SCIENCE FACILITIES, SEMI-CLOSED LIFE SUPPORT SYSTEM, AND MANY NUCLEAR POWER SOURCE



It is important to note the quantity of water shown here may be high because a small percentage of the water measured in the early Apollo samples (used to derive this data) may have been influenced by water contamination when returned to and analyzed on Earth. Also, there would be additional requirements to purify the water obtained. Oxygen may be obtained from further processing of CO and CO<sub>2</sub>. The effect of supplying Lunar Base consumables from He-3 mining on the overall Lunar Base scenario development can be seen in Figure 4-2. To accurately compare the two He-3 mining scenarios, similar criteria must be applied. Both scenarios have similar He-3 production rates for each year. Both mining concepts assume mass delivery increases of 25% from one year to the next. Both concepts are capable of obtaining 1000 kg of Lunar He-3 per year by the start of the fourth phase of the Lunar Base (year 23).

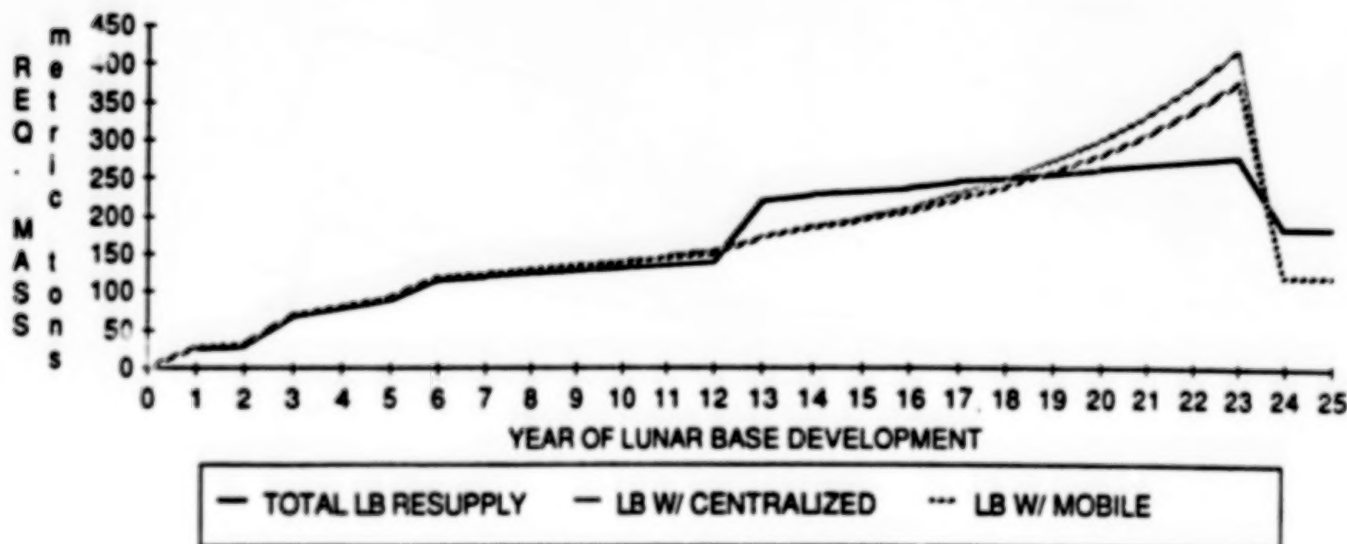
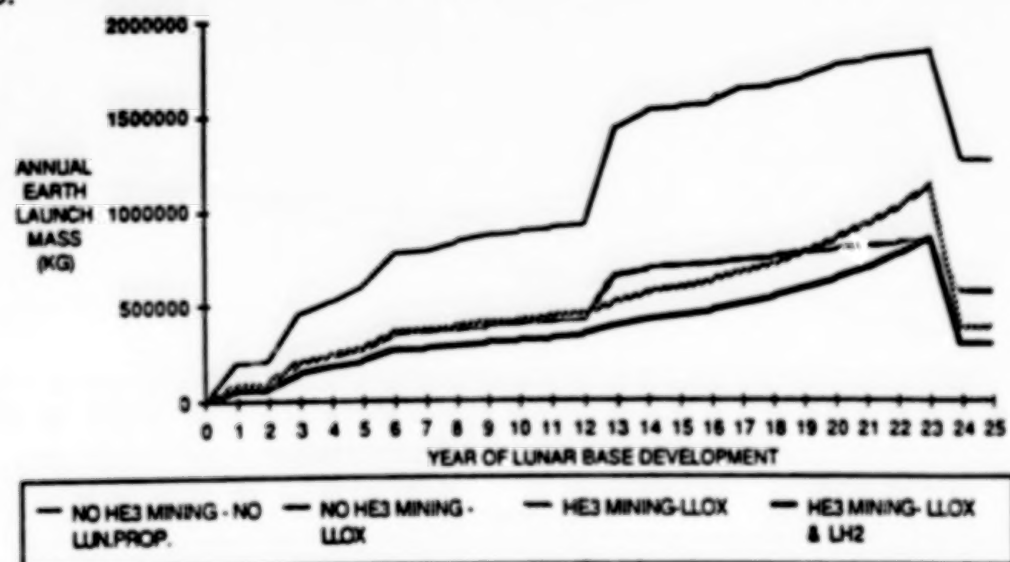


FIGURE 4-2. LUNAR BASE RESUPPLY WITH AND WITHOUT INTEGRATION OF HE3 ACQUISITION SCENARIOS

The mass delivery for a Lunar Base with He-3 mining is actually less than the baseline Lunar Base (without He-3 mining) for He-3 acquisition rates of 100-300 kg/yr and a Lunar Base with 10 permanent crew. This occurs because the He-3 mining operation can resupply the Lunar Base with consumables for life support, atmosphere maintenance, and manufacturing and production processes. In addition to resupplying consumables, the centralized concept delivers all the excavation equipment needed for manufacturing and production operations in the fourth phase of the Lunar Base. The fourth phase is reached by the 23rd year of base development, but hardware delivery for this phase is begun at year 13. After year 23, no expansion of operations is assumed and the Lunar Bases with the He-3 mining operations operate with reduced logistic requirements compared to the baseline case. Also, the effect of He-3 mining will be even greater when a lunar-derived source of both hydrogen and oxygen have been realized in the space transportation system design. The total Earth launch mass per pound of payload to the moon may be reduced by 50% with this source of propellants available (Crabb, Jacobs, Teeter, 1987).

Another measure of the effects of Lunar Base concepts on the space infrastructure is the amount of mass needed to be launched from Earth to deliver all payloads, transport vehicles and other support needs to the Moon. To determine Earth launch mass, the Lunar mass delivery curves (Figure 4-2) are used to

generate an annual mission model. The mission model is then manifested on orbital and launch/landing vehicles that are conceptually defined using ASTROSIZE. ASTROSIZE is a computer model used to design conceptual vehicles from propulsion system characteristics, aerobrakes, landing systems, thrust structures, etc. Total propellant and vehicle requirements are accounted with various sources of propellants considered. The mission model, with space transportation vehicle descriptions (including OTV and lander design), is entered into ASTROFEST. ASTROFEST is a computer code which uses the mission model and vehicle descriptions to determine quantities of Earth propellants, Lunar propellants, and overall Earth launch mass required. Here, the vehicles are sized to account for availability of lunar oxygen and lunar hydrogen if they are available. From these data, the total support of Lunar Base concepts may be evaluated based on the total Earth launch mass including payloads, propellants and vehicles. The results are shown in Figure 4-3.



**FIGURE 4-3. TOTAL EARTH LAUNCH MASS FOR LUNAR BASE AND LUNAR BASE WITH HE3 ACQUISITION**

The results of the Earth launch mass analysis show that He-3 acquisition can reduce the Earth launch burden of establishing a Lunar Base through the provision of consumable gases and propellants. Without He-3 acquisition, O<sub>2</sub> is the most likely propellant candidate from Lunar sources. With He-3 acquisition, H<sub>2</sub> can also be obtained as a by-product and used for propellant. Using H<sub>2</sub> and O<sub>2</sub> from Lunar sources provides enough credits to the Lunar Base with He-3 acquisition to make this scenario less resource intensive than the baseline Lunar Base without He-3 acquisition.

#### 4.3 Increase in Lunar Base Commercialization Potential

In addition to reducing resupply requirements, He-3 acquisition would enhance the commercialization potential of the Lunar Base in several ways. The He-3 could be used provide large quantities of power to a Lunar Base or for the support of other space exploration missions. The by-products could be used by the entire space community. Quantities of He-3 could also be shipped to Earth to support the nuclear energy economy of the 21st Century with the safest known fusion reaction.

##### 4.3.1 Space Markets for He-3 and He-3 Acquisition By-products

As fusion technology advances, many new applications of He-3 will be determined. Researchers are already investigating fusion powered space transportation vehicles. In addition to transportation, quantities of He-3 could provide sufficient power to conduct tasks that would require large amounts of power. A central power plant on the Lunar surface operating on a D-He3 fusion cycle could beam sufficient energy to

run a space station in Low Lunar Orbit. This power plant could also beam energy to other locations on the Lunar surface, thus extending the Lunar Base's range of operation. This energy could also be used to establish and operate other base camps.

A more immediate market that He-3 acquisition opens up for the Lunar Base is the availability of the by-products of He-3 acquisition. By the 10th year of Lunar Base development, excess quantities of He-3 acquisition by-products could be made available for the support of other space activities. These activities include: 1) resupply of the space station with life support and atmosphere maintenance consumables at many times lower cost than delivering from Earth; and 2) Providing needed resources for a Lunar refuel/resupply station for support of other space exploration missions. Figure 4-4 shows the quantities of by-products that could be made available for uses other than the support of a Lunar Base.

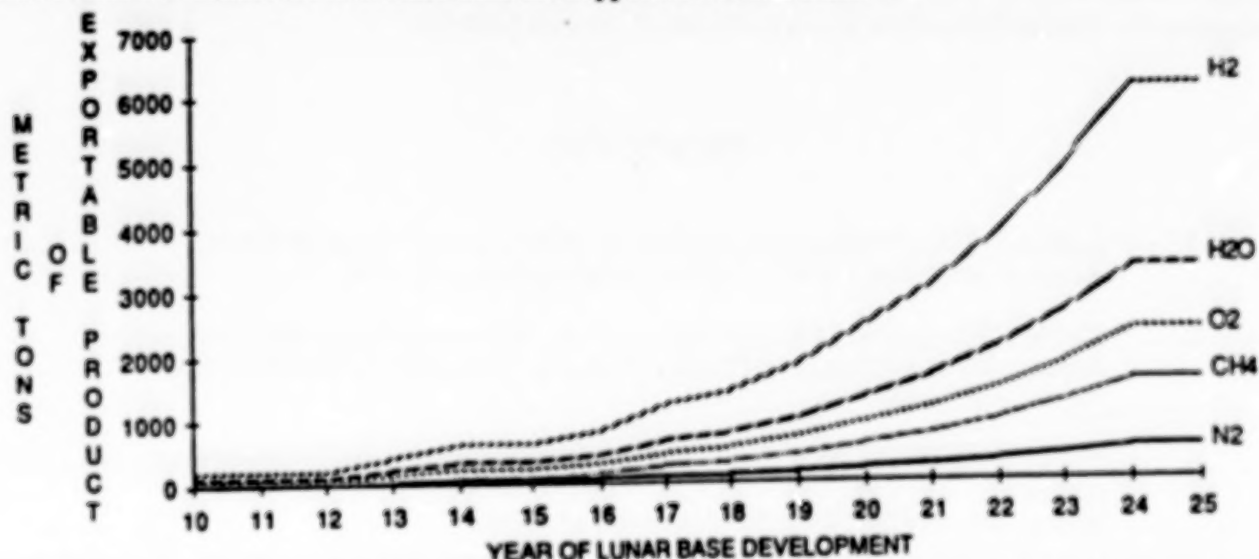


FIGURE 4-4. ANNUAL PRODUCTION OF EXPORTABLE RESOURCES FROM LUNAR HE-3 ACQUISITION BY-PRODUCTS

Many other applications of the resources He-3 acquisition makes available may be discovered as manned presence in space grows. The availability of these resources definitely enhances the feasibility of many space exploration missions.

#### 4.3.2 Terrestrial Market for He-3 as a Fusion Fuel

As the 21st Century approaches and fossil fuel supplies diminish, Earth's economy will require much greater amounts of power and energy. Nuclear power does seem to be an answer to the problem but the safety hazards associated with fission reactors has sparked sufficient public concern to hold up development of more nuclear power plants. Nuclear fusion has significantly lower safety risks, and the D-He3 cycle has the lowest safety risk factor of any of the known fusion cycles. Terrestrial quantities of He-3 are not sufficient to support large scale D/He-3 fusion power development, Lunar He-3 is abundant enough to support large scale fusion power on Earth and may provide a strong impetus to return to the moon on a commercial and cost effective basis.



## 5.0 SUMMARY AND CONCLUSIONS

Here we have shown the value of He-3, a resource scarce on Earth but relatively abundant on the Moon. An evolutionary Lunar Base scenario was presented and impacts of two He-3 acquisition concepts on this base were determined. A centralized He-3 mining concept, where regolith is excavated and returned to a central facility where the He-3 is removed, did have a more significant impact on the Lunar Base than the mobile miner concept, where solar wind gases are extracted from lunar regolith and the gas storage vessels are returned to the central facility for further gas processing. The availability of He-3 acquisition by-products reduced operating requirements of a Lunar Base and provided the base with greater potential for commercialization by making these by-products available for the support of other space missions. Finally, lunar He-3 could support a terrestrial nuclear power economy with the lowest safety risk of any nuclear reaction known. This paper concludes that He-3 acquisition enhances the feasibility of establishing a permanently manned Lunar Base in the early part of the 21st Century.

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## COMMENTS ON DRAFT PANEL REPORT

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The following comments are based upon the rough draft of the panel summaries handed out on the morning of Tuesday, April 26, 1988 at the workshop, and on discussions within the Working Group I sessions on Monday afternoon.

### Comments on Summary

I feel it is a mistake to emphasize or advocate the incorporation of the  $D^3He$  reaction into existing devices and research programs. Most of these devices, tokamaks and stellarators, are low beta devices with relatively low magnetic fields. They are designed to approach breakeven only for the very reactive DT reaction. When one burns any other fusion reaction of lower reactivity in these devices, one immediately pays a penalty in power density. This can make the  $D^3He$  and other advanced fusion reactions appear less attractive than the DT reaction.

There should be much more emphasis in the summary on an entirely new class of high beta and/or high magnetic induction experiments that are specifically designed to burn advanced fuels at the same fusion power densities as tokamak reactors. I feel that the mention of burning  $D^3He$  in near term devices such as ITER, NET or the CIT should be omitted from the report. Even a very superficial analysis based on the parameters of these machines will show that the  $D^3He$  reaction is not competitive at these low beta's, either in terms of power density or total power output.

### State of the Art for $D^3He$ Analysis

I feel that this section should be completely rewritten. I would like to make the following points:

1. There is much more literature on  $D^3He$  design studies than was discussed at the workshop. To give the impression that essentially nothing has been done in the past is extremely misleading. I have appended a list, of which references one to three, and seven to nine are all specifically related to the  $D^3He$  reaction. My textbook, ref. 7, treats the  $D^3He$  and other advanced fusion reactions on equal terms with the DT reaction in both its physics and



technology related chapters. At the same time, I feel that it is fair to comment that additional detailed engineering design studies, even more complete than those by Baker et al. in ref. 9, need to be made for  $D^3He$ -burning major experiments, engineering test reactors, and utility powerplants. These studies should be based on high magnetic field and/or high beta reactor designs which are specifically intended to burn the  $D^3He$  reaction, and can thus be expected to demonstrate the advantages of this fusion reaction.

2. I do not believe that this report should go out without making the point that, after more than 25 years of research on the tokamak concept, it has accumulated a number of problems, like barnacles on a ship. These problems have slowed that program down, and probably made a fundamental reevaluation of the DT tokamak concept a desirable thing to do, now that the  $D^3He$  reaction is capable of providing an alternative.

I would like to make the following points about the difficulties with the tokamak concept as an electric utility powerplant reactor:

A. The tokamak concept does not operate in the steady state. According to current understanding of its physics, there appears to be no way that a reactor grade plasma can be operated steady state with known current drive concepts. This failure to operate in the steady state is very serious from an electric utility point of view. In utility applications, any cyclic thermal and mechanical stresses during operation will seriously degrade the lifetime of these highly stressed systems.

B. After more than 25 years of intensive theoretical research on tokamaks, physicists still do not understand how particles are transported from the inside to the outside of tokamaks. This is very serious, and is entirely unacceptable to those who must design billion dollar powerplants from first principles. The existing scaling laws for containment time of tokamaks are phenomenological in nature, and are only as good as their present database. They cannot be reliably extrapolated, and they are not in any way based on an understanding of the physical processes occurring in tokamaks.

C. The DT tokamak is restricted to values of beta lower than perhaps 6 or 8 percent. This means that to confine a given plasma, the tokamak makes very inefficient use of its magnetic field. The required magnetic fields in the plasma for DT tokamaks are approximately 8 tesla, which is barely within the capabilities of current superconducting magnet technology; for tokamaks burning such advanced fuels, as  $D^3He$ , the required magnetic fields at these values of beta are well above 10 tesla, values beyond the current state of the art for large coils.

D. Finally, the very careful engineering design studies which have been done of DT tokamak fusion powerplants, such as the STARFIRE study of ref. 6, indicate that the tritium inventory of DT tokamak powerplant reactors will be somewhere between 5 and 15 kilograms. The tritium inventory of the Starfire study was 11.6 kilograms, and the first wall and blanket inventory of activated material after one year of operation of STARFIRE was over six giga Curies. As pointed out later, these radioactive inventories are potentially

worse than Chernobyl in terms of radioactivity hazard. The DT tokamak must be assumed to be in serious trouble with public acceptance on that basis.

The above four points are only the major problems currently perceived with the DT tokamak reactor. Over the past 20 years of design studies, these problems have emerged, without uncovering any compensating major economic or environmental advantages. The existence of the above 4 major problem areas, I feel, is a necessary condition for a major reevaluation of the current direction in fusion research, and a sufficient reason for giving very serious consideration to reactors based on the  $D^3He$  reaction.

3. I feel it is very unwise to suggest that  $D^3He$  be incorporated into existing major experiments such as TFTR and JET, because these low beta, relatively low magnetic field devices were designed for operation with the highly reactive DT reaction. When operated with  $D^3He$ , their total power outputs and power densities will necessarily compare unfavorably with the DT reaction. At the very least, the point needs to be made that no definitive trial of the  $D^3He$  reaction should be performed in anything but a high beta/high magnetic field device specifically designed to burn that reaction.

## I-2 How Does the $D^3He$ Reaction Compare to DT?

The original questions put to Working Group 1 contained six items, only two of which are listed in the draft document. This is unfortunate because the original questions were more pertinent than many of the issues addressed in the draft document, some of which are relatively minor. I will first comment on the questions posed in the original document:

1. Physics Requirements - Contrary to the impression given in the draft document, much more has been done on the physics of the  $D^3He$  reaction, and the results are less controversial, than indicated. The physics of this reaction has been extensively studied in refs. 3 and 7 through 9. An example of these findings, taken from the National Academy of Sciences report of ref. 3, is shown in Figure 1. This is a Lawson diagram for self-sustaining fusion reactors. This study made a number of simplifying assumptions for the four fusion reactions shown. This self-sustaining fusion reactor is one in which the cold incoming fuel is heated by the energy of charged reaction products up to the burning temperature. This is a somewhat more demanding requirement than a scientific breakeven or Lawson reactor. One can see that the minima of these curves for the  $D^3He$  reaction is about a factor of 3 higher in the Lawson parameter, the product of the number density and containment time, and is approximately a factor of 4 higher in kinetic temperature. In a broad perspective of the history of fusion research, these are not large factors, with the mainline programs having progressed a factor of 100 in kinetic temperature, and more than a factor of 1,000 in Lawson parameter, in the last 25 years.

2. Fueling - I agree with several other members of the panel that fueling is likely to be a minor issue for both the DT reaction and all advanced fuel reactions. The issue of fueling, whether a major or minor technological

problem, is not likely to be significantly different for the DT and other fusion reactions.

**3. Power density** - I do not agree that the relevant parameter is the total power generated, divided by the total reactor core mass, when it comes to comparing the DT with advanced fusion reactions. This index or performance parameter is very likely to favor the advanced fuels, because of their reduced requirements for blanket mass. However, individuals in the electric utility business are accustomed to looking at the core power densities in megawatts per cubic meter. This issue of power density constraints is discussed extensively in chapter 9 of ref. 7, from which Figures 2 and 3 are taken. It is shown in Chapter 9 of ref. 7 that, as the result of a variety of economic and engineering constraints, the fusion power density of fusion reactors is likely to lie between 1 and 10 megawatts per cubic meter whether they burn DT or an advanced fuel. Above 10 megawatts per cubic meter, the neutron or thermal wall loadings are likely to burn out the first wall; below 1 megawatt per cubic meter, the fusion power densities are so low that an uneconomically large reactor is likely to result. A large majority of fusion powerplant design studies have come up with reactor designs in which the fusion power density is between these limits. These limiting power densities define a region on the ion number density-kinetic temperature plane which is shown in Figures 2 and 3. In these figures, a plasma stability index, beta, of 20% is assumed, and the resulting operating lines for magnetic inductions in the plasma from 2 to 8 tesla are shown.

Figure 2 indicates that to burn the  $D^3He$  reaction, at magnetic inductions of 8 tesla or below, and in the range between 1 and 10 megawatts per cubic meter, a beta of 20% or larger is required. Figure 3 indicates that for this same range of fusion power densities, the DT and catalyzed DD reactions also can be burned with magnetic inductions below 8 tesla. A more extensive parametric analysis given in Chapter 9 of ref. 7 indicates that if one is restricted to magnetic technologies of 8 tesla (in the plasma) and below, then a plasma stability index beta of 20% or more is required for the  $D^3He$  reaction. With the same constraint on the magnetic induction, the DT reaction can be burned at plasma stability indices as low as 5%. If one demands the same fusion power density from whatever fusion reaction is being considered, then there must be a tradeoff between plasma stability index and magnetic induction. A magnetic containment concept capable of stable operation at betas of 20% or higher must be used if one is restricted to state-of-the-art magnetic inductions of 8 tesla or lower. However,  $D^3He$  could be burned at plasma stability indices of 5%, characteristic of the tokamaks, if magnetic inductions of 15 to 20 tesla were feasible.

**4. Heat Flux** - The heat flux issues are relatively minor. It is shown in Chapter 9 of ref. 7 that only DT reactors are likely to be limited by neutron wall loading. All other fusion reactions, including the catalyzed DD and the  $D^3He$  reactions, are going to be limited by the thermal wall flux. Whatever the fusion reaction, first wall loadings are going to be the dominant constraint on the power density and hence the economics of a fusion reactor. Right now there is concern within the DoE fusion program about the materials implications of fluxes of 14 MeV neutrons; if we are serious about the



development of the  $D^3He$  reactor, attention should be paid to the analogous problem of increasing the thermal wall loading limits for such reactors. This should be a much easier job than the neutron wall loading problem, since thermal wall loadings and heat transfer research are a well developed area of powerplant technology.

5. Materials Issues - I found it surprising that the extensive study of first wall and blanket issues done for 5 different fusion reactions, including the  $D^3He$ , by Charles Baker and the Argonne group [Ref. 9], was not referred to or utilized in the report. This work was funded by the DoE, involved 10's of person-years of effort, and is the closest approximation in the literature to a detailed powerplant design study which compares various fusion reactions under a common set of input assumptions. This study at Argonne indicated quite clearly the many safety, environmental, and materials advantages of the  $D^3He$  reaction. Some of the findings of this study are summarized in Chapter 14 of ref. 7, on pages 534 through 539. This study concluded that the shielding thickness was reduced by about a factor of approximately 2 for the  $D^3He$  reaction as compared to the DT reaction.

6. Plasma Heating - The differences between DT and advanced fuel plasma heating requirements are likely to be relatively minor. If we can heat a DT plasma up to 10 keV, essentially the same technologies should be able to heat the same plasma up to 40 to 60 keV required to ignite the advanced fuel reactions. This issue is probably not worth mentioning in the final committee document.

7. Current Drive - I think it is a bad mistake to even mention the subject of current drive, because this is an issue which is very serious for the tokamak concept, but it is not a generic problem of either advanced fuels or of most magnetic containment concepts unrelated to the tokamak. To try to say that there is a significant difference in the physics of the current drive between DT and such advanced fuels as  $D^3He$  is a red herring at this point because it is not known how to maintain tokamak currents in the steady state. This ignorance applies to all fusion reactions, including the DT.

8. Efficiency - I agree that the energy conversion efficiency possible by direct conversion is likely to be much higher for the  $D^3He$  reaction, which releases essentially all of its energy as charged particles. This is an important selling point for the  $D^3He$  reaction, since the DT or catalyzed DD reactions release a large proportion of their total energy in the form of neutrons, the energy of which must be recovered by relatively inefficient thermal cycles.

9. Licensing and Acceptability - For reasons outlined below, I believe that the difference between the licensing and acceptability of the DT and  $D^3He$  reactors are likely to be so large quantitatively that they will be perceived by the public as being different qualitatively. It would not surprise me if the public found the tritium inventories and the activated material from the blanket and first walls in DT tokamak reactors to be unacceptable. If it is presented fairly to public bodies, the  $D^3He$  reaction should be acceptable.

## Original Issues Addressed to Working Group I

At this point I would like to revert to the original questions put to the working group, which are not the questions addressed in the final draft document which I have discussed above. I have already discussed the physics requirements, which was the first of six issues that the panel was asked to compare for the DT and  $D^3He$  reactions. The remaining 5 issues, which were not adequately addressed in the draft statement, are as follows:

### I - 2-B Radiation Safety

The likely difference between fission and fusion radiological hazards is enormous. On Table 1 are shown data taken from references 4 to 6, and 9 on this issue. The first column shows the source terms, in Curies, for the Chernobyl accident, which will be a benchmark for all future discussions of nuclear hazards. The Chernobyl accident released into the atmosphere about 50 megacuries of biologically inert noble gases, and about 50 megacuries of biologically active elements which may enter the food chain. At the time of the Chernobyl accident, the reactor's core inventory was about 1500 megacuries. This can be compared with the STARFIRE study, a very extensive engineering design of a DT tokamak powerplant which was published in 1980 and represented several hundred person-years of effort [Ref. 6]. That study arrived at a total inventory of tritium of 11.6 kilograms, or 111 megacuries. That study also indicated that after one year of operation, the STARFIRE DT tokamak would have a total inventory of over 6 gigacuries of activated first wall and blanket material.

About two years prior to the STARFIRE study, the same group at Argonne studied the relative effect on first wall and blanket issues of burning the DT and other advanced fusion reactions [Ref. 9]. They concluded that the entire tritium inventory of a  $D^3He$  reactor could be held to less than 50 grams, or 0.5 megacuries, thus making the use of a containment vessel unnecessary according to NRC guidelines. They also concluded that the total throughput of tritium would be no more than 5 grams per day for the  $D^3He$  reactor. This amount compares with about 350 grams per day for the DD reaction, 50 grams per day for the catalyzed DD reaction, and 5.1 kilograms per day for a DT fusion reactor. The numerical differences compared in Table 1 are so large quantitatively that they become a significant qualitative difference between the  $D^3He$  and DT reactions. The source term data on Table 1 makes it very hard for the fusion community to justify a DT tokamak powerplant on environmental grounds, or to make the case that fusion is better, in safety terms, than fission. While it is true that the biological of tritium is far less than the heavy radioactive elements released during the Chernobyl accident, public perception of relative risks is very likely to be more closely related to the source term in Curies, than it is to the biological hazard potential. Comparison of the second and third columns of Table 1 is also significant, because the numbers were arrived at by the same engineering group at Argonne, using similar input assumptions. It thus appears that while the volatile radioactive inventory of the STARFIRE DT tokamak is 111



megacuries, more than twice the source term of the Chernobyl accident, the total radioactive inventory of a  $D^3He$  reactor would be less than half a megacurie (already 100 times less than the Chernobyl release), and perhaps much less if precautions were taken to get the 5 grams of tritium produced per day out of the reactor rather than stored as inventory in the blanket and shield.

I do not feel that this panel should be hesitant to bring forward the numbers in Table 1 in a public discussion of the relative merits of  $D^3He$ . It is clearly far superior in terms of both volatile source term inventory, and of activated wall, blanket, and shielding materials.

#### I-2-C - Waste Removal and Storage

This issue is also addressed by Table 1 above. The STARFIRE DT tokamak and essentially all other DT reactors operating at the gigawatt level, are likely to produce as many or more Curies of core inventory as fission reactors; It then becomes difficult to justify the DT reactor as being radiologically superior to fission power. About 10 years ago, a number of first wall and blanket studies were done by Powell at the Brookhaven National Laboratory, which indicated that a  $D^3He$  reactor, burning rich in helium 3, and using SAP as a wall and blanket material, could permit hands-on maintenance after shutdown. Clearly, both fission and DT fusion reactors are very far away from hands-on maintenance. Even if ordinary engineering materials are used in  $D^3He$  reactors, one can anticipate total radioactive inventories far less than those of the DT reaction. This issue of the relative activation of different fusion reactions was also extensively addressed in ref. 9, another important source of materials information for  $D^3He$  reactors which was not adequately discussed in the panel deliberations.

#### I-2-D - Power Generation

As was mentioned in the summary document, the fact that the  $D^3He$  reaction releases essentially all of its energy in charged reaction products should allow very efficient conversion of the fusion energy to electricity.

#### I-2-E-Timeframe to Demonstration of Principle and Commercialization

It was stated several times during the working group discussions, but not in the summary document, that the technology for the  $D^3He$  reaction could be based on state-of-the-art, with very few or much less difficult developmental problems than those needed to handle the 14 MeV neutrons associated with the DT reaction. It was the conclusion of many members of the working group, including myself, that the time necessary to achieve the physics parameters for the  $D^3He$  reaction will be much more than compensated for by the saving in time for the development of the technology required to burn the  $D^3He$  reaction.

## I-2-F - Cost

There are two cost issues here; the first is the cost of developing a  $D^3He$  fusion reactor, and the second issue is the cost, once development has been paid for, of an individual  $D^3He$  fusion powerplant, as compared with a DT, fission, or fossil fuel powerplant of the same capacity.

One can make, I think, a good case that the developmental cost of a  $D^3He$  reactor is going to be less expensive than a DT reactor, because it should take less time to develop in the absence of 14 MeV neutron technology issues. The cost of an individual gigawatt level  $D^3He$  fusion powerplant is likely to be much less than that of a DT or fission powerplant of the same capacity for reasons implied by the source term comparisons of Table 1. If a  $D^3He$  reactor can be built that does not require a containment vessel, or in which hands-on maintenance is possible, then the cost per plant is certainly going to be much less than that of a plant for which a containment vessel is required (with all of its licensing implications), or in which remote maintenance is needed.

## Near Term Plasma Validation Issues

This section of the draft document was not called for among the original questions addressed to the working group. In addition to the minor point made in the draft document, I would like to make the additional point that if  $D^3He$  is considered at all, it should only be after a very searching examination of the current status of the DT tokamak program. If  $D^3He$  is developed, the program should not repeat the mistakes of the DT tokamak, and, for example, proceed in complete ignorance of the physical mechanism by which particles are transported from the inside to the outside of a  $D^3He$  plasma. Such is certainly no basis on which to proceed to design billion dollar facilities. The plasma-related issues which are likely to be important for the development of the  $D^3He$  reaction are, in my view, as follows:

1. The physical process responsible for radial transport in  $D^3He$  plasmas must be understood, and the confinement time scaling known. A broadly based, multi party, intensive research program should be developed to understand the physical process responsible for radial transport in fusion grade plasmas, and this should be known before any more large machines are built.

2. A steady state, high beta ( $\beta > 0.2$ ) confinement concept should be developed for the burning of advanced fuels. The fusion community should not rely on the development of magnet technologies above 8 tesla to assure power densities of practical interest; such technologies are going to be very difficult to engineer because of the high levels of stress involved, even if they should be feasible. At present, there are a very large number of magnetic containment concepts from which to choose. In Chapter 11 of ref. 7, 18 distinct toroidal magnetic confinement concepts are discussed, and in Chapter 12 of that reference, 23 distinct nontoroidal magnetic containment concepts are discussed. Many of these are capable of operating at high values of beta, and

several of these can operate in the steady state. I believe that the fusion community should be satisfied with nothing less than a steady state, high beta magnetic containment concept for burning advanced fuels. Steady state operation is desirable in order to avoid thermal and mechanical stresses from cyclic operation; high values of beta, above 20%, are desirable in order to efficiently utilize the magnetic field and achieve useful power densities without having to require inordinately high magnetic inductions, above 8 tesla.

An intensive and extensive program of small-scale experiments designed to develop steady state high beta confinement concepts should be implemented right away in order to have these concepts available at a future time when the fusion community is forced by environmental concerns to develop fusion reactions other than DT. Steady state, high beta magnetic containment geometries are already well known; the EBT concept produced plasmas with betas up to 50% in the steady state, and the earth's magnetosphere is another example. The value of beta for the earth's magnetosphere is close to unity, it confines plasma routinely in the steady state, and individual particles in the magnetosphere, with MeV energies, have been observed to be confined for periods of years. Surely an intensive and properly directed research program could uncover other steady-state, high beta confinement concepts which would make both the physics and technology much easier for the future development of advanced fuels.

#### V - Questions

The thrust of most of these questions relates the development of  $D^3He$  technology to existing or planned DT tokamak experiments. I feel that it is a bad mistake to even suggest testing the  $D^3He$  reaction in low beta, low magnetic field devices not designed for that reaction. We should make clear from the start that the  $D^3He$  reaction requires either higher values of beta or higher magnetic inductions than reactors burning the DT reaction. If we propose anything that is perceived as a paired comparison or a crucial test in a low beta, low magnetic field tokamak, the resulting low power densities of the  $D^3He$  reaction will probably be used as an argument against proceeding with the  $D^3He$  reactor. We should probably insist on the development of a steady state, high beta magnetic containment concept as part of an overall package required to burn the  $D^3He$  reaction. I do not think that it is sensible, or technically honest, to imply that the  $D^3He$  reaction can be usefully burned in low beta devices, where the resulting power densities are never going to be above 1 megawatt per cubic meter and will probably be far lower.

I also do not like the emphasis in this section of the document on high magnetic inductions for the burning of  $D^3He$ ; Usable magnetic technologies above 8 tesla simply are not now available. On the other hand, there are existing examples of steady state, high beta magnetic containment concepts, such as the earth's magnetosphere and the EBT, which indicate that either those or similar concepts could easily be developed, thus making unrealistically high magnetic inductions unnecessary.



### **I-3-How does Helium 3 Compare to Lithium as a Blanket Material in DT Fusion?**

I personally feel that it is foolish to take an expensive, radioactively stable and environmentally acceptable fuel like  $^3\text{He}$ , and convert it into tritium, a volatile radioactive gas, which is certain to get the fusion community into trouble with anti-nuclear advocacy groups. Already, the Sierra Club has issued a policy paper opposing the use of tritium. I therefore am very surprised at a serious proposal to deliberately make trouble for ourselves by creating tritium, when we could be burning the  $^3\text{He}$  directly. Also, during the deliberations of the working group, I did not hear a satisfactory explanation of why it would be advantageous to use as a breeding medium  $^3\text{He}$ , which might cost a hundred million dollars per kilogram or more, instead of lithium, which costs only a few tens of dollars per kilogram. This tremendous difference in the breeding material cost is going to appear throughout the entire lifetime of a fusion powerplant, and must necessarily have a significant impact on the cost of power. During our entire discussion of this matter no one suggested any advantages or cost savings associated with the use of  $^3\text{He}$  in the blanket which would come even close to making up this tremendous difference in fuel operating cost.

While I feel that some detailed first wall and blanket design studies should be done to identify the cost and advantages of using  $^3\text{He}$  as a tritium breeding material in fusion blankets, I do not think that it is sensible or wise to open ourselves to criticism by seriously proposing to convert  $^3\text{He}$  into tritium.

### **Issue P-1 Social Implications of Mining $^3\text{He}$ from the Moon**

One issue which I did not hear discussed during the final plenary session was the desirability of basing the energy supply of the entire earth on a fuel that had to be imported from outer space. The human race should probably not get itself into a position in which, if a nuclear war or other major social disruption were to occur, all of the world's powerplants would have to be shut down for lack of fuel. The maintenance of a space flight capability is certainly one of the highest and most technically complex achievements of the human race; the ability to mine and transport  $^3\text{He}$  from the moon to the earth is very likely to be among the first things disrupted by a major war or other social disaster. Some way needs to be found to build up very large reserves of  $^3\text{He}$ , or otherwise assure that if the  $^3\text{He}$  supply were disrupted, this would not automatically shut down energy generation all over the planet. Such a major shutdown of fusion energy in the future might very well lead to deindustrialization, and an irreversible reversion to barbarism.

### **Issue P-3 Other Factors not Addressed by this Workshop**

In the worldwide fusion community, there is a widespread mindset which one can characterize as "DT chauvinism", according to which it is

considered disloyal to the national fusion program, or even a disservice to the entire subject of fusion energy, to point out any of the very real engineering or safety disadvantages of using the DT reaction. I have personally encountered this mindset while advocating advanced fuel reactions at meetings within the fusion community, and some of the remarks made during this workshop also appeared to be based on this mindset. In many cases, this mindset probably arises from a lack of awareness or misunderstanding of the many technical advantages of advanced fusion reactions; a feeling that the world fusion effort is so deeply committed to the DT reaction that they are technically beyond the point of no return; that it is not useful to consider any other fusion reaction regardless of technical merits for political reasons; a feeling that any questioning of the DT reaction strengthens the position of the critics of nuclear and fusion energy; and that it is some how politically unproductive to compare DT with other fusion reactions, lest the existence of some disadvantages be used to the detriment of fusion energy as a whole. I think that most members of this workshop are well aware of this DT chauvinism, and this form of technical inertia will probably be the single worst obstacle to adoption of  $D^3He$  or any fusion reaction other than DT.

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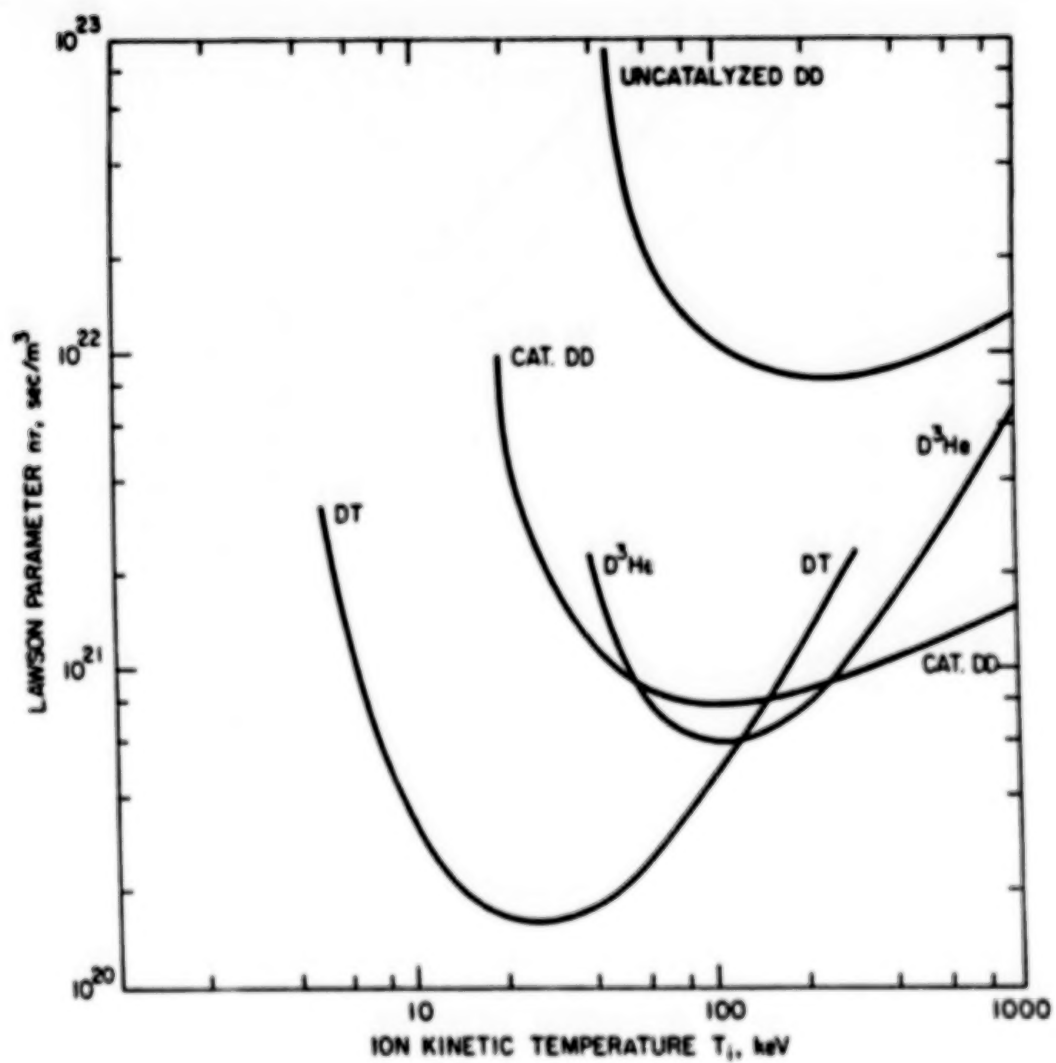


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TABLE I

FISSION AND FUSION RADIOLOGICAL HAZARD COMPARISON

REACTOR CHARACTERISTIC	CHERNOBYL ACCIDENT	STARFIRE DT TOKAMAK	D <sup>3</sup> HE REACTOR AND BLANKET
Biologically inert (Noble) gas release	~ 50 MCi	—	—
Biologically active radiation release	~ 50 MCi	—	—
Tritium Inventory	—	~ 111 MCi (11.6 kg)	< 0.5 MCi (< 50g)
Core/Blanket Inventory	~ 1500 MCi	6140 MCi	—
Reference	4,5	6	9



LAWSON DIAGRAM FOR SELF-SUSTAINING FUSION BURNS

FIGURE 1

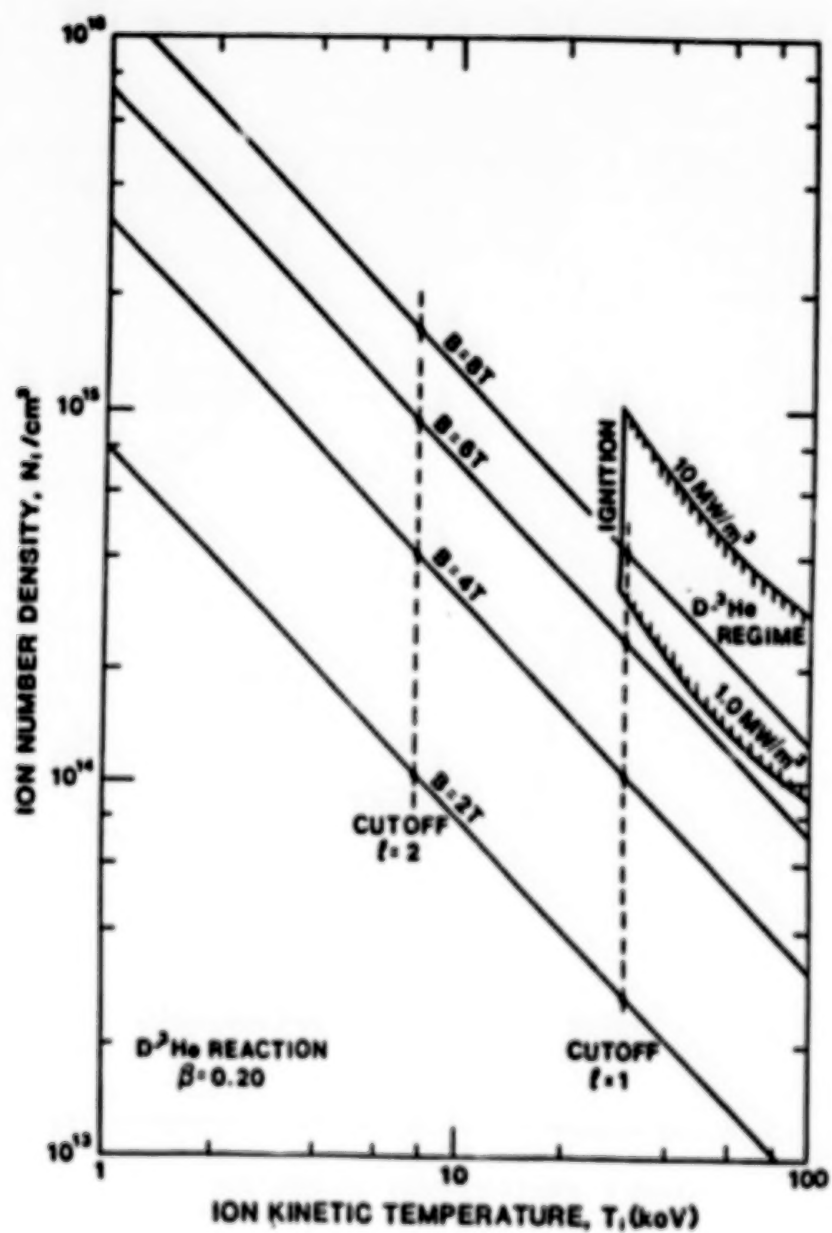


FIGURE 2

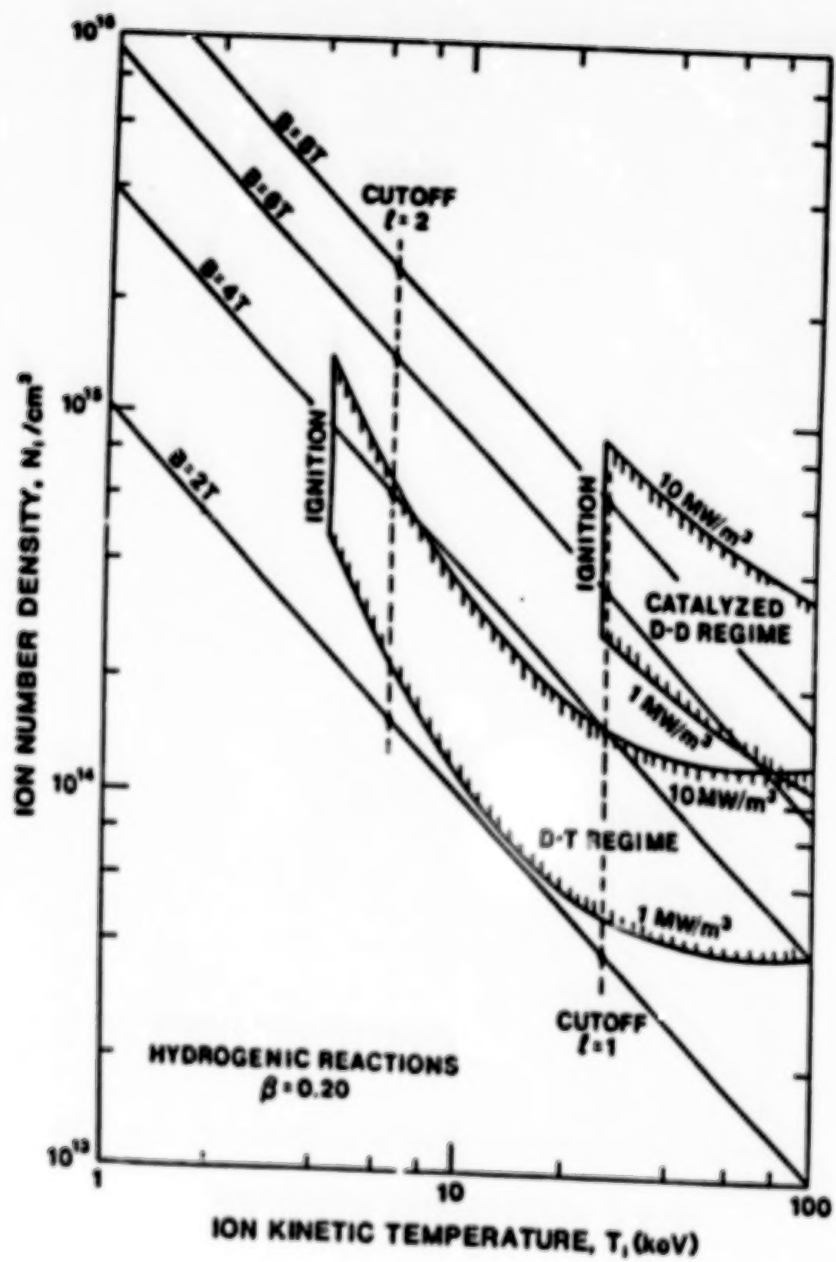


FIGURE 3

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ASSESSMENT OF LUNAR SOURCES OF He-3 FOR USE ON EARTH

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## SUMMARY

As a gross measure of the economics of mining lunar sources of He-3, the energy densities (GJ/ton) of lunar soils were compared with the energy densities of various existing and future terrestrial sources of energy. On this basis, only the very richest lunar ores appear competitive with coal. Future lunar exploration might emphasize identification of lunar soils having higher concentrations of He-3.

## INTRODUCTION

Because of the currently rising interest in possible use of  $^3\text{He}$  from the Moon as a source of energy on Earth (ref. 1), assessment of the economics of this potential energy source is also of growing interest. A small effort has already begun to assess the cost of energy supplied in this way (refs. 2 - 3). In general, the existing studies have concentrated on the various unit operations for such an enterprise and estimated the cost of each unit of activity.

I suggest another approach to assessing the overall cost of this fusion energy, namely, to compare the energy densities (GJ/ton) of various terrestrial energy sources with the energy density of lunar soil containing  $^3\text{He}$ . Because the processes of extracting and delivering energy from terrestrial and lunar sources differ so markedly, only in the crudest sense could one equate their economics. On the other hand, simply a gross comparison of the comparative magnitudes can aid us in forming a perspective on this issue, key attractions being its directness and simplicity.

My purpose is to supply just such a comparison.

## LUNAR SOURCES OF $^3\text{He}$

Table IV in reference 2 lists the helium content actually measured in several samples of lunar soil returned by the Apollo missions and reported in reference 4. The concentrations cited there range from 17 to 360 grams of helium per (metric) ton of soil; the bulk of this helium is, of course, conventional  $^4\text{He}$  and not suitable for use in fusion reactors (as they are currently envisioned).

The concentration of  $^3\text{He}$  in He on the Moon was measured to be as high as 423 atoms of  $^3\text{He}$  per million atoms of He

(ref. 2, Table IV), roughly equalling the  $^3\text{He}$  fraction in the solar wind (ref. 2, Table III). Here on Earth, the concentration of  $^3\text{He}$  is 1.3 atoms of  $^3\text{He}$  per million atoms of He. I will bracket this entire range by assuming that the concentrations range from 1.3 to 423 atoms of  $^3\text{He}$  per million atoms of He.

In no mining operation is all of the desired material extracted, some losses inevitably occurring during the mining, during the beneficiation, and during the extraction processes. Those potential losses are ignored herein, 100-percent recovery of the  $^3\text{He}$  being assumed. Fusion of this  $^3\text{He}$  with D would produce 18.35 MeV of energy per  $^3\text{He}$  atom fused. Fusion of every atom of  $^3\text{He}$  is assumed herein, any losses being ignored. Because of these assumptions, the estimates herein of energy content of the lunar soil are optimistic.

Based on those assumptions, the energy contents of lunar soil are those shown in figure 1, ranging from 0.01 to 67 GJ/ton of soil.

#### TERRESTRIAL ENERGY SOURCES

The following terrestrial energy sources are considered:

Coal: Its energy content is taken to be 12,000 Btu per pound, or 28 GJ/ton.

Uranium: The concentration of uranium in its ore is taken as 100 grams of  $\text{U}_3\text{O}_8$  (yellow cake) per ton of ore, and each fission releases 200 MeV of energy. Burner nuclear reactors are herein assumed to fission 1 percent of the U atoms present in the ore; in turn, the energy content of the ore is 69 GJ/ton. Breeder reactors are assumed to fission 50 percent of the U atoms present in the ore; in turn, their energy release is 3400 GJ/ton of ore.

D - T fusion: Each fusion of D and T produces 17.59 MeV of energy. The D content of water is taken as 150 D-atoms per million H-atoms. Complete fusion of this deuterium would produce 28,000 GJ/ton of water.

These energy contents for terrestrial sources are plotted in figure 2 along with the parallelogram for lunar  $^3\text{He}$  from figure 1.

#### DISCUSSION

Only the very richest lunar ores cited in reference 2 exceed coal in their energy density, and the principal range of lunar energy sources has energy densities far below that of coal. The leanest lunar ores are thus surely not economic as energy sources here on Earth.

On the other hand, lunar ores may well vary widely in their content of  $^3\text{He}$ , even as the terrestrial soils and rocks vary enormously in their composition. If so, lunar sources of  $^3\text{He}$  still undiscovered might have concentrations of  $^3\text{He}$  higher than shown in figure 1 and, in turn, have energy densities substantially exceeding that of coal. So we should still keep our minds open on this topic. But, it appears to me, considerable lunar exploration is required to locate richer deposits of  $^3\text{He}$  before we infer that the lunar sources of  $^3\text{He}$  will be economic to mine and to transport back to Earth as terrestrial energy sources.

Even though this comparison of terrestrial and lunar energy sources has, admittedly, a crude basis, its directness and simplicity aid in forming a view of the lunar sources. In future studies of the concepts for mining  $^3\text{He}$  on the Moon, special attention should be given to estimating the costs of this mining and transportation so that we might improve on the assessment herein.

#### CONCLUDING REMARKS

Comparison of the energy densities (GJ/ton) of terrestrial sources of energy with those for  $^3\text{He}$  on the Moon show that only the richest currently-known lunar sources are even marginally competitive with the terrestrial energy sources. If such lunar sources are in the future to compete economically with the terrestrial energy sources, lunar exploration is required in order to locate richer deposits of  $^3\text{He}$ .

On the other hand, utilization of lunar sources of  $^3\text{He}$  may prove advantageous for space propulsion even if these sources are uneconomic for terrestrial application.

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# ENERGY CONTENT OF LUNAR SOIL

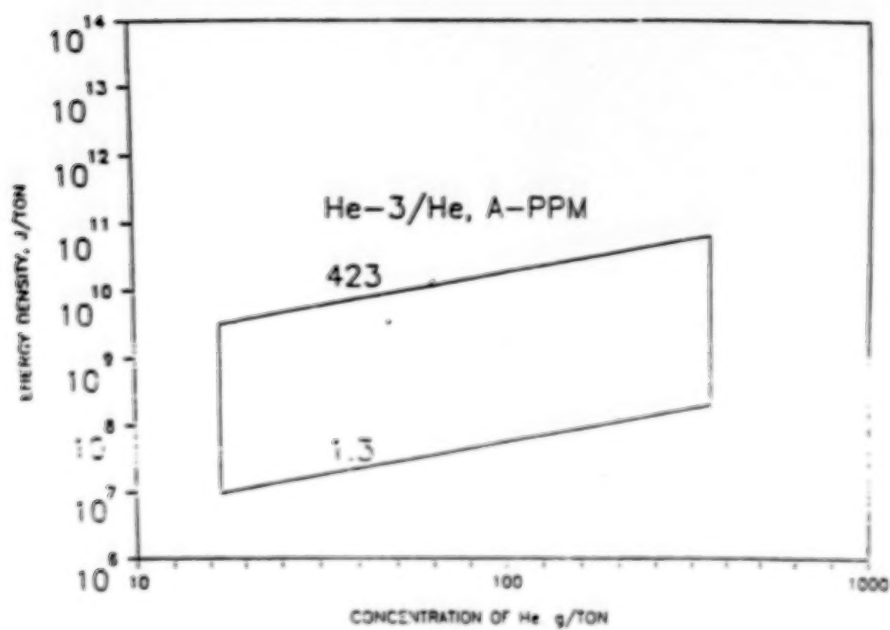


Figure 1

# TERRESTRIAL ENERGY SOURCES

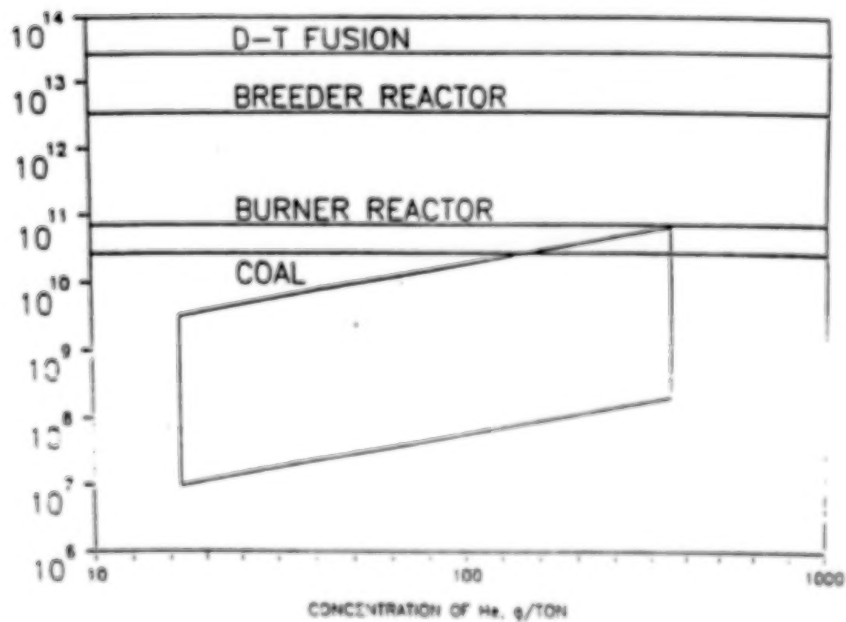


Figure 2



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